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GASIFICATION OF SOLID FUELS IN GERMANY BY THE LURGI, WINKLER, AND LEUNA SLAGGING-TYPE GAS-PRODUCER PROCESSES

BY

WILLIAM W. ODELL

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By William W. Odell[2]

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[1] The Bureau of Mines will welcome reprinting of this paper, provided the following footnote acknowledgment is used: "Reprinted from Bureau of Mines Information Circular 7415."

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INTRODUCTION

Certain gas-making processes are in use in Europe, particularly in Germany, which differ radically from those in common use in America. A number of them are of particular interest because they are different. The questions naturally arise: Are any of them applicable to the making of gas in this country and, if so, with what particular type of solid fuel? It is a fact that some of them were developed with consideration of a particular set of conditions and for the utilization of solid fuels available in Germany. The latter fuels, in certain characteristics, are unlike the high-rank fuels commonly used for making gas in the United States; therefore, in attempting to evaluate the various foreign-developed processes with regard to usefulness here, one must give attention to the particular conditions that will prevail in any specified case and also the characteristics and requirements of the process and generator under consideration. Three of the processes that were developed and put into commercial operation in Germany, and which have some characteristics in common, are considered in particular in this publication; they are:

1. Lurgi pressure gasification process.
2. Winkler process.
3. The Leuna slagging-type producer-gas process.

Each of these processes requires steam and oxygen as gas-making fluids.

For a number of years, oxygen has been used in a relatively pure state, along with steam, in making gas in Germany, and many of the difficulties initially encountered have been overcome. Although it appears that oxygen recovered from air was first used in this manner as a method of utilizing a byproduct in a plant that used the nitrogen complement in the manufacture of ammonia; more recently, the oxygen was made particularly for the purpose.

The fuels - brown coal or lignite - used in processes 1 and 2 were not suitable for use in the older and commonly used intermittent-type water-gas generators, and it was necessary, therefore, to devise a different process for gasifying them. A gas of higher heating value than producer gas was desired, and the use of oxygen (not air) along with steam made possible the production of the desired gas without nitrogen dilution, which characterizes producer gas.

Operating data presented herein are based upon observations by members of the Technical Oil Mission at plants in Germany, on records, and on information vocally given to members of the Mission, including the author, while visiting those plants, and they are believed to be reasonably correct; however, certain basic observations, comparisons, and conclusions are made by the author.

ACKNOWLEDGMENTS

The information relating to the operation of the various processes used in Germany and described in this circular is from notes made by the author while on an inspection tour of the various plants as a member of the combined Technical Oil Mission of the British and United States Governments and by reference to the drafts of the following reports:

Report on Investigations by Fuels and Lubricants Teams at the I. G. Farbenindustrie A. G. Works at Leuna, edited by R. Holroyd, C. I. O. S. Item 30, File XXXII-107, issued also as Bureau of Mines I. C. 7370.

A. G. Sachsische Werke, Bohlen (near Leipzig), Germany, reported by H. Hollings, C. V. Hopton, L. L. Newman, W. A. Horne, and E. Spivey, C. I. O. S. Item 30, File XXX-13.

Report on Investigations by Fuels and Lubricants Teams at the Brabag Works at Troglitz-Zeitz, edited by J. F. Ellis and R. J. Morley, C. I. O. S. Item 30, File XXXIII-24.

The author expresses his thanks and appreciation of the cooperation of the other members of the teams who visited the various plants in which the Lurgi pressure gasification process, the Winkler process, and the Leuna slagging-type producer-gas process were investigated. The personnel of the teams was as follows:

Visitors to the Leuna Plant.

For the British Ministry of Fuel and Power: H. Hollings, J. F. Ellis, H. G. Simpson, G. U. Hopton, R. Holroyd, M. A. G. Banks, D. A. Howes, A. J. V. Underwood, R. A. Taylor, and R. J. Morley.

For the U. S. Petroleum Administration for War: E. B. Peck, P. K. Kuhne, H. M. Weir, V. Haensel, E. Cotton, W. F. Faragher, J. G. Allen, H. Schindler, W. A. Horne, and J. P. Jones.

For the Bureau of Mines: L. L. Hirst, W. W. Odell, and L. L. Newman.

Visitors to the Troglitz-Zeitz Plant.

For the British Ministry of Fuel and Power: J. F. Ellis, H. Hollings, G. U. Hopton, L. King, and R. J. Morley.

For the U. S. Petroleum Administration for War: G. S. Bays, Jr., W. F. Faragher, W. A. Horne, J. P. Jones, P. K. Kuhne, B. L. MacKusick, and H. M. Weir.

For the U. S. Foreign Economic Administration: E. B. Peck.

For the Bureau of Mines: L. L. Hirst and W. W. Odell.

Visitors to the A. G. Sachsische Werke at Bohlen.

For the British Ministry of Fuel and Power: H. Hollings, G. U. Hopton, H. Bardgett, J. F. Hurley, J. G. King, E. Spivey, and A. J. V. Underwood.

For the U. S. Petroleum Administration for War: G. S. Bays, Jr., W. A. Horne, J. P. Jones, P. K. Kuhne, B. L. MacKusick, and H. M. Weir.

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THE LURGI PRESSURE-GASIFICATION PROCESS

The Lurgi pressure gasification process is, in effect, a continuous water-gas process; it is carried out in a water-jacketed generator, usually under pressures ranging from 10 to 20 atmospheres. In the ordinary water-gas process employing steam and air as the gas-making fluids, the operation is necessarily intermittent or cyclic, because the heat required to promote the reaction of steam with carbon can not be supplied by simultaneously blasting the hot fuel bed with air and steam, because of the resulting dilution of the gas with nitrogen. When oxygen is substituted for air, it is not necessary to alternate the gas-making run periods and air-blasting or heating phases of the cycle, and the oxygen and steam may be introduced into the fuel bed simultaneously as a common stream. In the latter case, it is necessary to proportion the amounts of steam and oxygen in the stream so that sufficient heat is supplied by the exothermic reactions of the fuel with oxygen to support the desired gasification reactions.

Major Reactions Involved

It is of interest to note the nature of the major reactions with which one is concerned in making gas in the Lurgi generator. Briefly, it may be said that the operation comprises promoting the water-gas reactions under pressure, which so changes the equilibrium conditions that more or less methane is formed, according to the pressure and temperature maintained in the generator. The chief chemical reactions involved are represented by equations (1) to (10), as follows:

Reactions	Heat of reaction[3]	
	B.t.u. on the pound-molar basis	B.t.u. per 1,000 cubic feet of dry gas made
(1) $C + H_2O = CO + H_2$	- 75,535	- 99,910
(2) $C + 2H_2O = CO_2 + 2H_2$	- 76,920	- 67,830
(3) $CO + H_2O = CO_2 + H_2$	- 1,385	- 1,830
(4) $C + 1/2\ O_2 = CO$	+ 47,570	+ 125,850
(5) $C + O_2 = CO_2$	+ 169,290	+ 447,855
(6) $C + CO_2 = 2CO$	- 74,150	- 98,080
(7) $2CO + 2H_2 = CH_4 + CO_2$	+ 106,250	+ 140,540
(8) $CO_2 + 4H_2 = CH_4 + 2H_2O$	+ 109,020	+ 288,415
(9) $CO + 3H_2 = CH_4 + H_2O$	+ 107,635	+ 284,750
(10) $C + 2H_2 = CH_4$	+ 32,105	+ 84,925

[3] Reactants and products at 60° F., are carbon as a solid (graphite), water as liquid, and the others gaseous. Values used are based upon data given by D. D. Wagman, J. E. Kilpatrick, W. J. Taylor, K. S. Pitzer, and F. D. Rossini in Free Energies, and Equilibrium Constants of Some Reactions Involving O_2, H_2, H_2O, C, CO, CO_2, and CH_4: Jour. of Research, National Bureau of Standards, Research Paper RP-1634, vol. 34, 1945, pp. 143-161. Heat liberated is designated by a plus (+) sign.

A little consideration of these reactions will be helpful to a better understanding of the results obtained in the operation of the Lurgi generator; hence they are presented here but are discussed briefly in somewhat general terms.

Equations (1) and (2), the well-known steam-carbon reactions, occur at a high rate at temperatures above about 900° C. (1,652° F.), the rate of reaction decreasing rapidly as the temperature falls below this level. The use of pressure in conducting these two reactions is not helpful. In other words, at a given high temperature ordinary water gas can be made as effectively at atmospheric pressure as at higher pressures. Of course, the reaction of equation (1) represents the results usually sought in preference to those of equation (2), hence the duration of the gas-generating period of the ordinary water-gas cycle is commonly selected, so that only a relatively small amount of the latter occurs; as the temperature decreases during the gas-making period, the relative amount of reaction (2) increases. A typical water gas made from coke by methods in common use in the United States is shown in column 1 of table 1. Although the heat requirements in promoting reactions (1) and (2) are of the same order of magnitude, and the amount of combustible gas made is the same in each case, it is noted that the mixed gas ($CO_2 + 2H_2$) produced according to reaction (2) is one-third inert carbon dioxide, and that twice as much steam is reacted in equation (2) as in equation (1) per unit volume of combustible gas made.

To make the process continuous, it is necessary to supply the heat of reaction during the gas-making period. One procedure for doing this is to introduce oxygen along with the steam. The amount of oxygen (O_2) required is of particular interest, not only because it is expensive but because its use alters the composition of the gas made. The exothermic reactions of equations (4) and (5), typifying the oxidation of carbon, show the amounts of heat evolved by its combustion. It would be desirable, in one sense only, if the oxygen employed were consumed by reaction (5), because more heat is evolved per mol of carbon dioxided and less O_2 is required per unit of heat energy evolved. However, at high temperatures, in the presence of carbon, reaction (4) will predominate, or, to be more exact, reaction (6) occurs, whereby the carbon dioxide (CO_2) evolved by reaction (5) combines with additional carbon to form carbon monoxide (CO). At usual gas-making temperatures all of these reactions, (4), (5), and (6), will occur when O_2 is introduced into an ignited fuel bed, and the net result will be the generation of heat amounting to a minimum of 47,570 B.t.u. per mol of carbon oxidized by O_2; the heat actually generated will be between 47,570 and 169,290 B.t.u. Equilibrium conditions for the major reactions encountered in the generation of water gas are so well understood that for a given temperature in the fuel bed and sufficient time for the water-gas reactions to reach equilibrium, the composition of the resulting gas mixture can be computed accurately. However, equilibrium conditions are not always reached in making gas at high rates, and this fact has important bearing not only upon the variation in composition of the gas made but in some cases upon the suitability of certain processes and fuels in the manufacture of gas for particular purposes. For the purpose of economy it is usually desirable to make gas by employing high rates of flow of the gas-making fluids in the generator, and it is frequently desirable to maintain moderately low temperatures in the fuel bed because of low softening temperatures of the fuel ash;

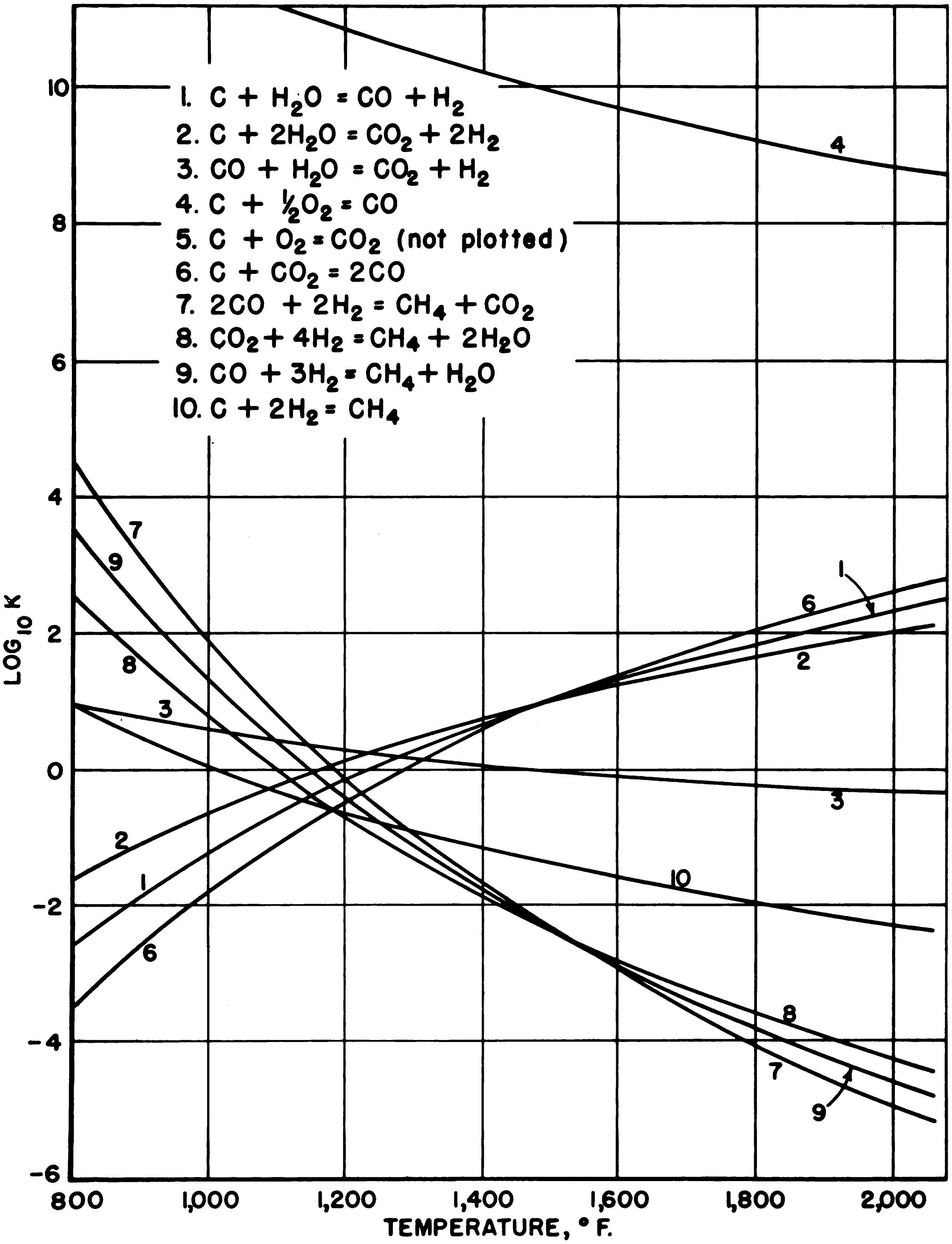

Figure 1.—Variation of the logarithm of the equilibrium constant ($\log_{10}K$) with temperature for several reactions involving O_2, H_2, H_2O, C (graphite), CO, CO_2, and CH_4.

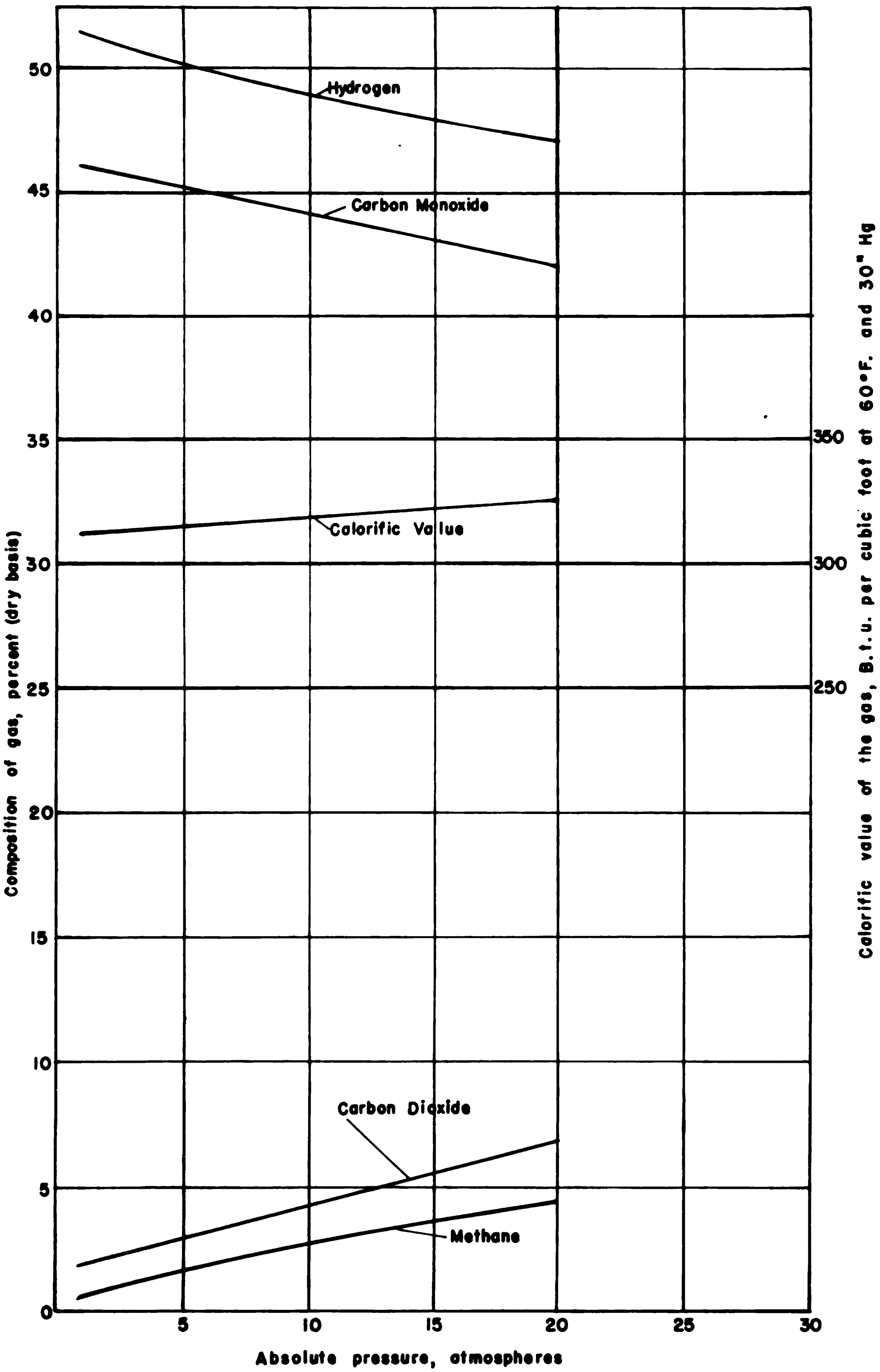

Figure 3.- Variation with pressure in composition and calorific value of water gas made when steam alone is reacted with carbon at 1,832°F. (1,000°C.), approximations from equilibrium values.

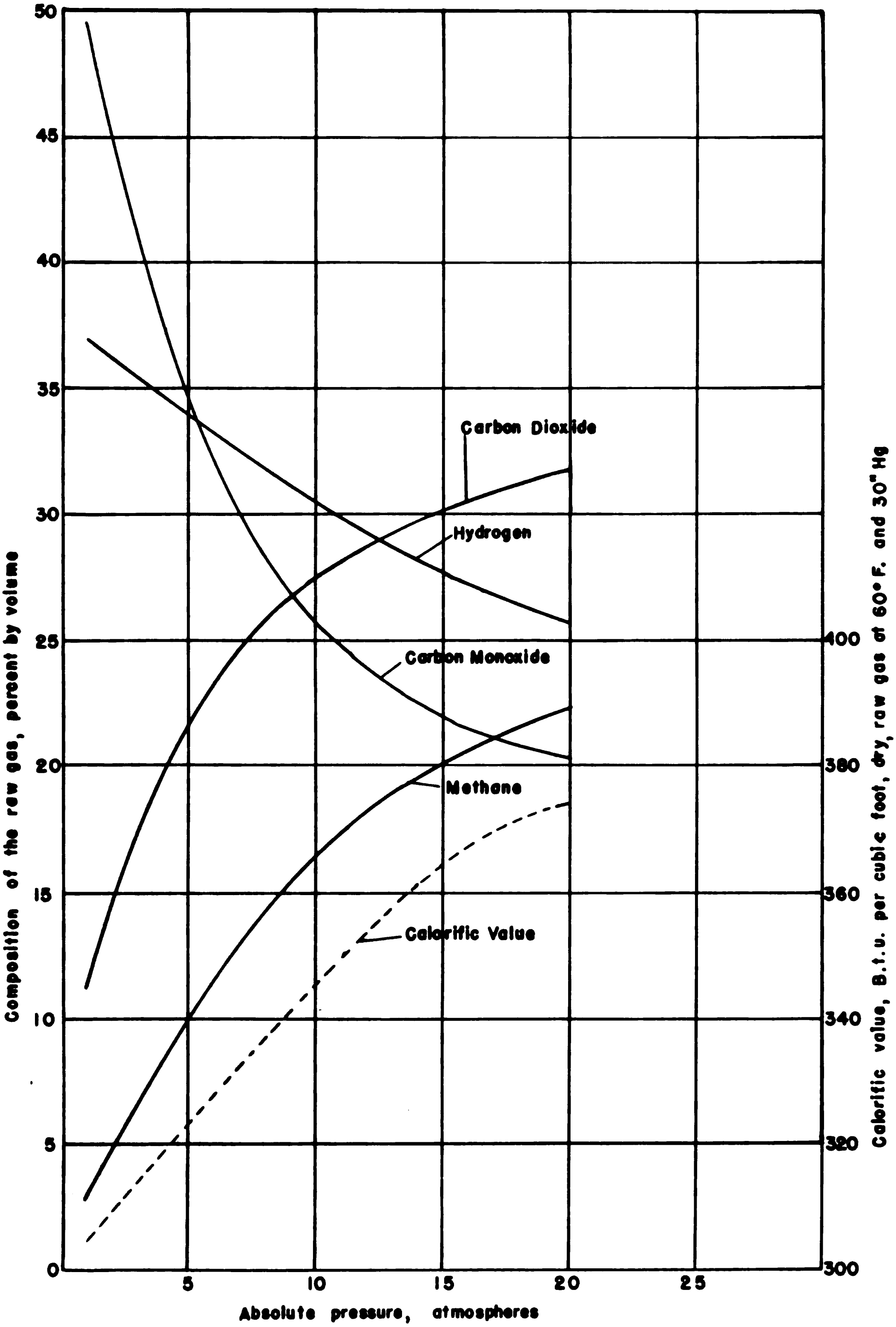

Figure 4.-Variation with pressure in composition and calorific value of raw gas made by gasifying reactive coal at 1,340° F. (1,000° K.) with oxygen and steam as gas-making fluids.

under these conditions reaction rates in the generator are low, and a state of equilibrium is not attained. It follows that the reactivity of the fuel is an important factor governing the degree of completeness of reactions and the composition of the gas made. A study of the basic gas reactions enumerated above with reference to these variables is helpful in understanding the reasons for certain operations employed in making gas by processes described in this publication.

Figure 1[3] shows the logarithm of the equilibrium constants for the reactions shown by equations (1) to (10). Although the rates of reaction are not indicated by the curves in this figure, the effect of changes in temperature upon the equilibria are clearly shown. In making ordinary water gas by reactions typified by equations (1) and (2), experience has shown that, at the average prevailing high temperatures the net result is substantially 90 to 92 percent of (1) and 10 to 8 percent of (2). Perhaps a more accurate statement of fact would be that the CO_2 formed by reaction (2) at high temperatures reacts with carbon of the fuel bed according to equation (6). The computed approximate composition of water gas made from carbon at equilibrium is shown in figure 2, over an appreciable range of temperature. The formation of CH_4 by reactions shown in equations (7) to (10) occurs to a limited extent only at high temperatures, whereas at low temperatures and at atmospheric pressure the latter reactions do not proceed at a rate usually considered sufficiently rapid for commercial application. Actually, in the low-temperature range of figure 2 some CH_4 is formed, but in actual commercial operations the amount formed at atmospheric pressure is less than indicated by the CH_4 curve, because the rate of reaction is normally slow and equilibrium is not approached.

Effect of Pressure upon the Composition of Gas

In the instance under particular consideration here, namely the production of gas in a Lurgi generator, the temperature of the fuel bed is rather low, for reasons which will become evident; hence, one must consider not only the nature of the gas that would be formed when a state of equilibrium is reached at the given temperature and pressure, but also the probability of approaching such a state when gas is generated at reasonably high velocity. The change in composition due to the use of O_2 with the steam must also be considered. Figure 3 shows the computed composition and calorific value of gas made when steam alone is reacted with carbon at 1,000° C. (1,832° F.) at different pressures; the values plotted are not absolute but are believed to be accurate enough to indicate the effects of change in pressure at the given temperature. It is obvious from the latter figure that as the pressure is increased reactions such as those shown, particularly in equations (7) and (10), occur increasingly; pressure favors these reactions. The total amount of CH_4 present, even at 20 atmospheres pressure and at the given temperature, is not large. Figure 4 is a plot showing variations in composition and calorific value of raw gas with change in pressure at 1,340° F., employing O_2 and steam as gas-making fluids; the plot is based upon theoretical values established by the German engineer Otto Hubmann.[4] The temperature chosen for making this plot was lower than that used in figure 3, and, therefore, the conditions are more favorable for the formation of CH_4 when chemical equilibria are reached. In actual operation, one would expect the amount of methane formed to be lower than that shown in figure 4, and such was found to be the case. The hot zone or region of the fuel bed in which the combustion reactions of O_2 with the fuel are initiated and consummated is thinner in the Lurgi process than in ordinary practice making water gas. Furthermore, employing coals of low ash-softening temperatures and maintaining a maximum temperature in the fuel bed lower than the ash-softening point, there is a large volume of relatively low-temperature fuel through which the gas passes in the generator. Under these conditions one would expect to produce a gas containing less CO, more CO_2, and somewhat more H_2 than shown in the gas compositions in figure 4. Results obtained in practice are in accordance with expectations.

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[3] Wagman, Donald D., Kilpatrick, John E., Taylor, William J., Pitzer, Kenneth S., and Rossini, Frederick D., Heats, Free Energies, and Equilibrium Constants of Some Reactions Involving O_2, H_2, H_2O, C, CO, CO_2, and CH_4: Research Paper RP-1634, Journal of Research, National Bureau of Standards, vol. 34, February 1945, pp. 143-161.

Referring again to equations (7) to (10), it will be noted that they are not only favored by increase in pressure but they are exothermic; hence, as the pressure is increased and these reactions occur increasingly, more heat is liberated in the fuel bed by them, and accordingly less O_2 is required in making gas. In considering equations (1) and (7) collectively, one might express the result by equation (11) as follows:

$$(11)\quad 2C + 2H_2O = CH_4 + CO_2 \quad - 44{,}820 \text{ B.t.u.}$$

In this reaction, 2 mols of gas are formed with the absorption of only 44,820 B.t.u., whereas in equation (1) 75,535 B.t.u. are required in producing the same volume of gas. However, twice as much carbon and steam are required to satisfy equation (11) as equation (1), but the gas made in (11) is 57 percent higher in heating value. In equation (11) excess steam, high pressure, and relatively low temperatures are favorable for CH_4 formation, whereas at high temperatures the reaction does not occur, but instead CH_4 and CO_2 combine to form CO and H_2.

Actual operating data[5] indicating how the composition and calorific value of the raw gas, made by gasifying reactive coal with O_2 and steam, varies with change in pressure are shown graphically in figure 5. The analyses used in plotting the latter figure were corrected for small amounts of N_2 initially associated with the O_2 used. The fuel used in making the gas was small (3/32- to 7/32-inch) and comprised broken pieces of briquetted, partly dried brown coal containing 20 to 25 percent moisture. The figure shows that the CH_4 content of the gas increases rapidly with increase in pressure up to about 10 atmospheres, but from 10 to 20 atmospheres the rate of increase diminishes with increasing pressure. In other words, as the CO_2 and CH_4 increase, conditions are not so favorable for the formation of more CH_4. The calorific value of the raw gas likewise increases with pressure.

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[4] Hubmann, O., Metallges: Periodic Rev., No. 8, 1934, pp. 9-15.
[5] Danulat, F., Mitt. Metallges, No. 13, 1938, pp. 14-22.

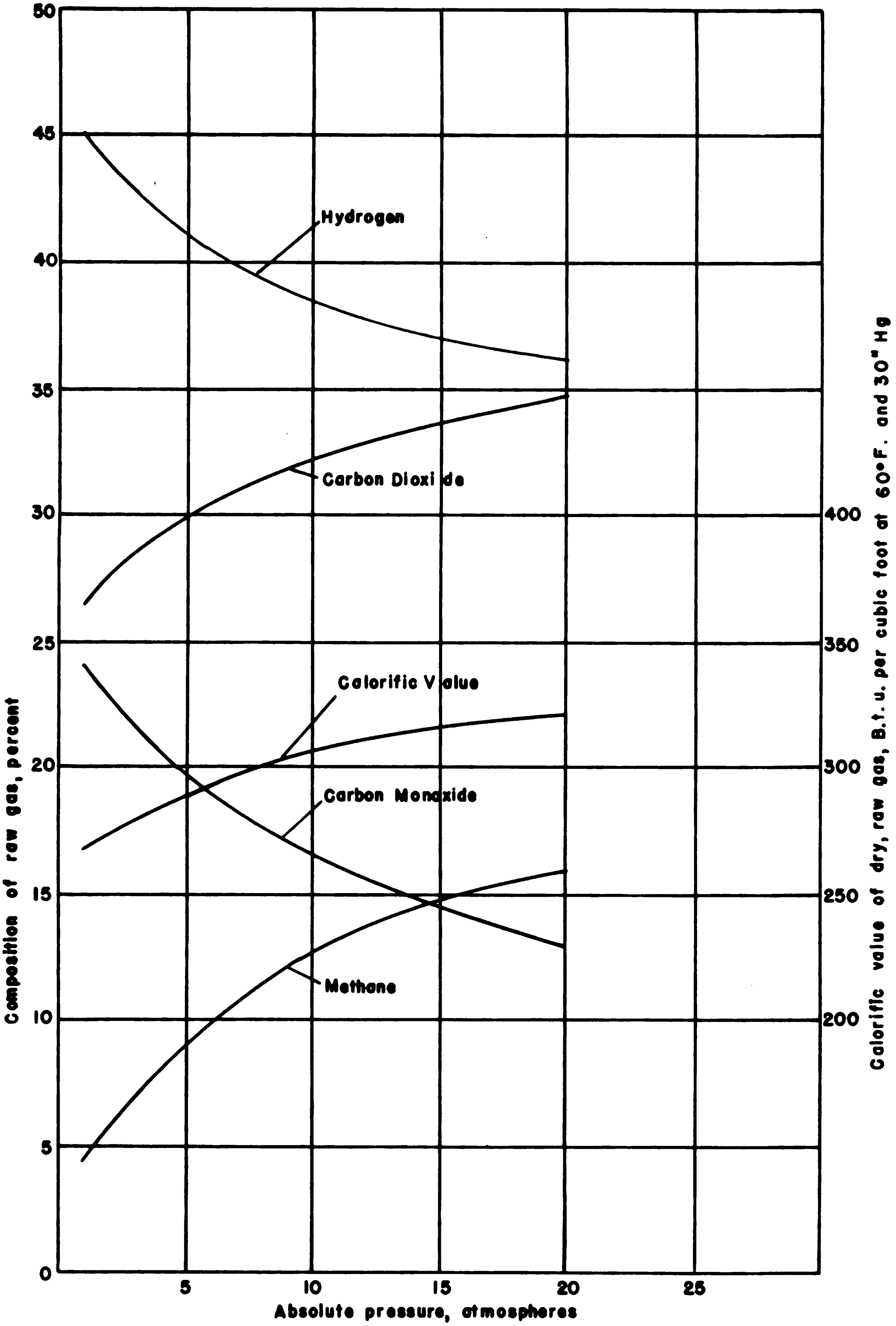

Figure 5.- Variation with pressure in composition and calorific value of raw gas as made in practice from brown coal, employing oxygen and steam as gas-making fluids.

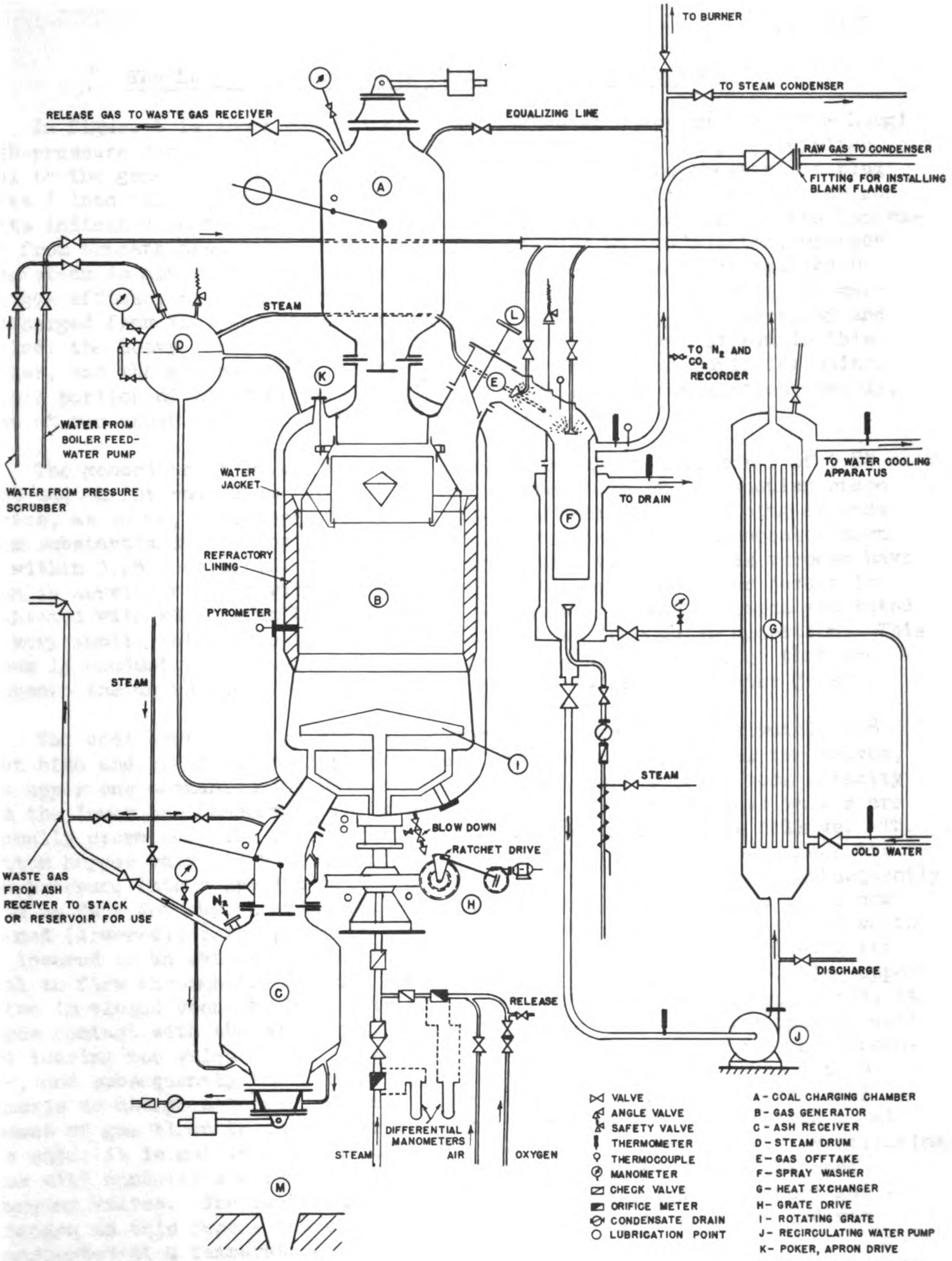

FIGURE 6.- DIAGRAM OF A LURGI HIGH-PRESSURE GENERATOR.

The Lurgi Gas-Generating Plant and Its Operation

In figure 6 is shown a sectional view, somewhat diagrammatic, of a Lurgi high-pressure gas generator and connections. The coal hopper, A, supplies coal to the generator, B, from which the ash is discharged beneath rotating grate I into ash reservoir C. Oxygen and steam are supplied through the conduits indicated to the hollow shaft, from which the mixture enters the generator from beneath the grate. The whole generator is water-jacketed, whereby some steam is generated and used as shown; the steam drum is designated D. The gas offtake, E, connects directly with a spray-cooler, wherein the gas discharged from the generator is immediately contacted by a water spray and cooled; the heavy tar condenses and is removed from the gas stream in this cooler, and the gas passes on to the regular scrubbing and purifying units. Only a portion of the generator is lined with refractory insulation, namely, that at and above the hottest portion of the fuel bed.

The generator is 16.40 feet high and has an external diameter of 9.84 feet and an internal diameter of 8.86 feet. The width of the annular space varies, as shown, from approximately 4.7 to 5.9 inches. The lining extends from substantially the top of the cylindrical portion of the generator down to within 3.25 feet of the grate. The fire bricks used for this purpose have been in service 4 years without replacement. Although the water jacket is connected with steam drum D of figure 6, the actual amount of steam generated is very small, being less than 132 pounds per hour in regular operation. This steam is conducted, as generated, directly to the gas offtake, so that the pressure inside the generator is the same as that within the water jacket.

The coal hopper, A, of figure 6 comprises a chamber approximately 9.8 feet high and 5.2 feet in diameter made of boiler steel. It has two valves, the upper one communicating with an overhead fuel bunker of 65 tons capacity and the lower one connecting the hopper with the generator; these valves are manually operated. The procedure for charging the hopper is as follows: The bottom hopper valve is closed, and the gas in the hopper is blown under its own pressure into a special holder provided for the purpose and is subsequently used as fuel for superheating the gas-making steam. The upper valve is now opened (lowered); this operation permits a cylinder supported by the valve to be lowered to an extent controlled by specially provided lugs, allowing the coal to flow through the cylinder from the bunker into the hopper. The upper valve is closed when the hopper is full. When the latter valve is raised, it makes contact with the movable cylinder, thus shutting off the supply of coal and leaving the valve clean. Gas is now let into the hopper from the generator, and subsequently the bottom hopper-valve is opened. It takes 5 to 6 minutes to charge a hopper, which is done about twice an hour. The total amount of gas blown to the holder from the hopper is 7 percent of the total gas made; it is not included in the reported volume of "make gas." Ventilating fans with conduits are provided to remove any gas escaping from the coal-charging valves. The coal bunkers are continuously purged with inert gas - nitrogen in this case - because the fuel used was highly reactive and was transported at a temperature of 80° C.

The top valve of the hopper, made of special alloy steel, seats against a rubber ring gasket which fits dovetailed into the top of the flange of the hopper. The normal life of this ring is about 3 months. The bottom valve of the hopper has a removable, conical, hard-steel insert, which contacts a chrome alloy-steel, sharp-edged seat, which is renewed yearly. The free opening of both valves is 10 inches.

A shield or skirt is provided in the generator beneath the coal inlet for the purpose of maintaining a free gas space above the fuel bed and supporting scrapers for removal of pitch and carbon from the upper wall of the generator. These scrapers are operated once every 1 to 2 hours for a period of 5 minutes. Inside of the skirt a conical ring is suspended, beneath which is a double cone for the double purpose of avoiding segregation of the fuel and equalizing the pressure across the fuel bed.

An essential step in operating the plant is to prepare the fuel, namely, crush, screen, and separate the dust and coarse particles from the desired sizes. Using the lignitic-type coal (Braunkohle) in Germany, the preferred sizes supplied to the generator are within the chosen limits, 0.12- to 0.39-inch. The coal as mined contains about 50 percent of water; a portion only of this water is eliminated by a drying operation before it is charged. It has been found desirable to leave 20 to 25 percent of moisture in the prepared fuel; it is fed to the fuel-supply hopper in this state.

Gasification is substantially continuous in the Lurgi generators. The time interval between charging the coal hoppers, which is, of course, dependent on their size, was approximately 20 minutes with the old generators at Böhlen, but with the new ones now in operation there the charging interval is approximately 40 minutes.

The grate is slightly domed and comprises three sections, in each of which is fitted a detachable portion that incorporates a plough arranged to direct the ash, which passes over the grate into a cylindrical space beneath the grate. A vertical vane, which is attached to the grate shaft, scrapes the ash into an offtake leading to the ash reservoir. The diameter of the grate is 5 feet 3 inches; the middle of the grate, on the top side, is 6 inches above the portion adjacent the generator wall. The grate sections are alloy steel (25 percent chromium) and are said to have a life of 3 years. The drive shaft of the grate is hollow to provide means for introducing a mixture of superheated steam and O_2 into the fuel bed. The grate is electrically driven by a 4.5-kw. motor connected with speed-control gearing and ratchet mechanism. The grate and driving mechanism are supported by the generator shell. The shaft is packed with metal-asbestos packing rings with provision for lubrication.

A bed of ashes is maintained in the generator to a considerable depth to protect the grate from rapid deterioration. Upon leaving the generator, the ash passes into the ash reservoir shown at C of figure 6, through a valve similar to the bottom valve of the coal hopper, except that its diameter is 1 foot instead of 10 inches. The ash reservoir is 9 feet 10 inches high and 4 feet 3 inches in diameter; its capacity is 124 cubic feet. The bottom of the reservoir is closed by a disk clamped by four swing bolts; a thin Klingerite packing ring set in the disk forms the actual joint and it is renewed after three discharges of ash. This reservoir is steam-jacketed, in part, to prevent condensation during cooling of the ash. The ash is discharged through a sieve into a water sluice approximately every 2 hours. When the pressure is released on the reservoir, prior to removing the ash, the oxygen and steam released pass into the atmosphere; whereas, after closing the reservoir the pressure is built up to working level by introducing live steam.

Apparently there have been no difficulties with clinker formation except during periods of irregular or abnormal operations; the ash as discharged is usually in fine granular condition. Clearly it is necessary that the temperature throughout the hot zone be lower than the ash-softening temperature at all times in order to avoid clinker troubles; this means that the temperatures must be carefully watched and controlled by proper adjustment of the relative amounts of steam and O_2 admitted to the generator.

The grate is rotated at a rate adapted to prevent excessive accumulation of ash, the speed being adjusted in accordance with the ash content of the fuel used and the rate of making gas. The usual speed is 1/2 to 2 revolutions per hour. The ash discharged contains 5 to 7 percent of carbon.

Using a fuel such as partly dried brown coal, containing 20 to 25 percent of water, the temperature of the gas leaving the generator is approximately 300° C. The gas contains tar and dust, which in the early stages of development of this process were troublesome. Various scrubbing methods were employed experimentally. The most satisfactory method thus far developed for solving these difficulties is the partial cooling of the gas by direct contact with water immediately after it leaves the generator and simultaneous promotion of rapid change in direction of flow of the gas stream; the means of accomplishing this are shown at F in figure 6.

The tar is discharged from the latter scrubbing device through a separate drain, and the excess water is recirculated through a heat-exchange cooler back to the scrubber. The gas enters the scrubber at about 300° C. under 20 atmospheres pressure and leaves at about 150° C. Subsequently, the gas passes through tubular coolers, wherein it is further cooled to 100° C., and then through baffle-type tar separators. Finally, after further cooling the gas, the condensed light oils are removed and the gas is oil-scrubbed for recovery of benzole.

The treatment of water gas for removal and recovery of tar and oil is not common practice in the United States for two reasons - (1) fuels that evolve tar and oil during the process are not commonly used, and (2) the temperature reached by the gas in the generating equipment is so high that the byproducts produced do not warrant their recovery. This statement does not apply to carbureted water gas or to gas made for special uses when it is necessary to remove certain byproducts.

After condensable products have been removed from the gas, the latter is scrubbed with water under pressure for the removal of CO_2 and H_2S. The total gas from the plant at Böhlen is passed in parallel through four scrubber towers packed with Raschig rings. The water, which is recirculated, is first delivered at high pressure to the scrubbing towers and then, after absorbing CO_2 and H_2S, it is expanded to atmospheric pressure through turbines similar to the Pelton wheels commonly used in this country for the same purpose. Subsequently the water from these scrubber towers is passed down through another series of four towers, which are packed with wooden grids while air is blown upwardly through the latter towers; this treatment removes the remaining H_2S from the water, conditioning it for recirculation. The air from the latter towers, laden with H_2S, is passed to the bottom of the powerhouse chimneys, where the H_2S reacts with SO_2 in the stack gas, forming sulfur, which is carried along in the stack gas and discharged into the atmosphere. After washing, the gas passes to Lux purifiers. These consist of two parallel sets of four boxes each, three of which are used while one is being recharged with oxide. The working life of a charge is approximately 4 weeks. The boxes are cylindrical, approximately 5 feet in diameter and 26 feet high; each contains 5 double trays with layers of oxide 16 to 18 inches deep, whereby the gas flows in parallel through the 10 layers in each box. The three boxes in use on each stream are worked in series. The gas entering the boxes contains 10 to 30 grams of H_2S per 100 cubic meters, which is equivalent to 4.1 to 12.3 grains per 100 cubic feet, and on leaving the boxes it contains 0.1 gram per 100 cubic meters, equivalent to 0.04 grain per 100 cubic feet. The amount of Lux purifying material used per annum was approximately 33 short tons. The total pressure loss in treating and purifying the gas was approximately one atmosphere.

Steam is supplied from the adjacent power station and is superheated to 500° C. by means of waste gas from the charging hopper and from the CO_2-removal plant before it enters the generators.

Oxygen is supplied from a Linde-Frankl plant on the premises. The latter plant comprises four units, two of which have a capacity of 37,000 cubic feet per hour and two 74,000 cubic feet per hour of free-oxygen measured as dry gas at 60° F. and 30 inches mercury pressure. The oxygen used is approximately 95 percent pure O_2 and is supplied to the generators under pressure of 23 atmospheres at 40° C. The power capacity of the oxygen plant is 4,600 kilowatts.

Some operating results making gas in the Lurgi pressure generator at Böhlen, Germany (average for month of January 1945):

Kind of coal used	Broken pieces of partly dried and briquetted braunkohle and partly dried braunkohle.	
Size of coal used	mm.	3 to 10 (about 1/8- to 3/8-inch)
(Not more than 5 percent under 3 mm. and not more than 10 percent above 10 mm.)		
Purity of O_2 used	percent	95
(Results are reported on the basis of quantity of equivalent pure O_2 used.)		
Composition of coal:		
Moisture	percent by weight	18 to 22
Volatile and fixed carbon	do.	70 to 74
Ash	do.	8.0
Total sulfur	do.	2.8
Divided: Sulfur in ash	percent by weight	1.2
Combustible sulfur	do.	1.6

Calorific value of the coal (high value)	B.t.u. per lb.	7,820 to 8,450
Speed of rotation of grate	revolutions per hour	1/2 to 2
Purified gas made month of January (measured at 60° F., 30 inches mercury pressure, dry)	cu.ft.	460,015,200
Purified gas made per day (measured at 60° F., 20 inches mercury pressure, dry)	cu.ft.	14,839,000
Purified gas made per generator, per hour, mean	cu.ft.	89,280
Rated capacity of generator per hour	cu.ft., dry gas	111,600
Total coal used per month	U. S. short tons	21,560
Total coal used per day	do.	695
Coal used per 1,000 cubic feet of purified gas	lb.	93.6
Oxygen used per day (measured at 60° F., 30 inches mercury, dry)	cu.ft.	2,158,700
Oxygen used per 1,000 cubic feet of purified gas made (measured at 60° F., 30 inches mercury, dry) (Oxygen is given as pure O_2; actually, somewhat larger amounts of 95 percent O_2 were used)	do.	146
Steam used, per month	U. S. short tons	20,001
Steam used, per day	do.	645.2
Steam used, per 1,000 cubic feet of purified gas made, to generator	lb.	87
Steam used, total per 1,000 cubic feet of purified gas made	lb.	114.9
Power consumption, per 1,000 cubic feet of purified gas made	kw.-hr.	7.36
Water used, per 1,000 cubic feet of purified gas	U.S. gal.	142

Average gas composition (January 1945):

		Crude gas	Purified gas
CO_2	percent by volume	32.1	9.1
H_2S	do.	1.6	0.0
Illuminants	do.	0.7	0.6
O_2	do.	0.2	0.2
CO	do.	12.1	16.7
H_2	do.	37.5	52.3
CH_4	do.	14.5	20.0
N_2	do.	1.3	1.1
		100.0	100.0
Calorific value (high value):			
Basis dry gas at 60° F., 30 inches mercury pressure	B.t.u. per cu.ft.	331.1	438.0
Basis saturated gas at 60° F., 30 inches mercury pressure	do.	325.3	430.4
Basis calorimeter test (calculated to dry gas at 0° C. and 760 mm.)	do.	-	a/432
Specific gravity (air = 1.0)		0.753	0.499

a/ The calorific value of the gas usually made at this plant is said to be about 5 percent higher than the above values, and the reason given was "bombing interfered with plant operations."

Purified gas made per square foot of equivalent grate area (area internal horizontal section), dry gas basis	cu.ft. per hr.	1,450
Purified gas yield per 2,000 pounds of coal:		
Saturated at 60° F. and 30 inches mercury pressure	cu.ft.	21,750
Dry gas at 60° F. and 30 inches mercury pressure	do.	21,370
Tar yield per short ton of coal	lb.	112.2
Tar yield per short ton of coal	U. S. gal.	14.0
Tar yield per 1,000 cubic feet of purified gas dry basis	do.	0.655
Benzine (light oil) yield per short ton of coal	lb.	48.4
Benzine (light oil) yield per short ton of coal	U. S. gal.	6.9
Benzine (light oil) yield per 1,000 cubic feet of purified gas, dry basis	gal.	0.323

Although the generators were operated at a mean hourly production of 1,450 cubic feet of gas per hour per square foot of equivalent grate area, the rated capacity is said to be 1,812 cubic feet per hour.

Capacity of the Lurgi generator and standard water-gas sets compared

The capacity of the gas-generating plant at Böhlen is approximately 5,670 million cubic feet of city gas per year. The plant comprises 10 generators, 5 of which were built in 1940 and 5 in 1944. The newer ones are improved as to the charging hopper, ash reservoir, grate-driving mechanism, and carbon scrapers. Although each generator is said to have a rated capacity of 111,600 cubic feet of purified gas per hour, they are actually producing 94,500 cubic feet per hour when operating at apparent capacity. It is also noted that thus far a generator could be operated 250 consecutive days, which included "time out" for 30 miscellaneous shut-downs totaling 90 hours. The total time lost for major and minor repairs is approximately 2,000 hours per year. It was stated by German engineers that some of the loss of time due to shut-down was occasioned by the war and use of slave labor. Accordingly, estimates based upon the actual capacity to produce gas must take into consideration necessary shut-down time. The dry purified gas has a calorific value of 438 B.t.u. per cubic foot, as shown above; hence, true capacity comparison can best be made upon the basis of a chosen standard calorific value. Such a comparison is made in table 1.

The values used in making this comparison are not the possible maximum but represent results attainable in good gas-works practice. The table shows that on the therm basis the Lurgi process, making gas at 20 atmospheres pressure, is comparable, as to daily capacity, with a standard water-gas generator of the same inside diameter. The capacities given in columns (5) and (2) of the table are not strictly comparable, because in a carbureted water-gas set not all the gas is made in the generator. However, because one of the unique features of the Lurgi process is the possibility of producing city gas without the use of oil for enrichment, it is interesting to make the comparison. In the carbureted gas shown in column (2), approximately 3.3 gallons of gas oil are consumed in the carbureting step per 1,000 cubic feet of finished gas, and in making a carbureted water gas of 483 B.t.u. per cubic foot, the oil required would be 2.2 gallons. Thus, the possibility exists of reducing the enricher-oil requirements by the latter amount in making city gas.

TABLE 1. - Composition of water gas and Lurgi pressure gas and the comparative production capacity[a] of the respective generators

	Ordinary water gas	Carbureted water gas	Lurgi high-pressure gas (20 atmospheres pressure)			
	Coke fuel	Coke fuel	Raw gas	Purified gas	Purified gas, CO_2-free	Purified gas at rated generator capacity
Percent:						
$CO_2 + H_2S$	5.5	4.4	33.7	9.1	0.0	9.1
Illuminants	.2	10.0	.7	.6	.7	.6
O_2	.0	.0	.2	.2	.2	.2
CO	40.0	32.0	12.1	16.7	18.4	16.7
H_2	50.0	35.0	37.5	52.3	57.5	52.3
CH_4	.8	14.8	14.5	20.0	22.0	20.0
N_2	3.5	3.8	1.3	1.1	1.2	1.1
	100.0	100.0	100.0	100.0	100.0	100.0
B.t.u.[b] dry gas	303	570	333	438	483	438
Mean hourly capacity[a]:						
Cubic feet per square foot of equivalent grate area	2,290	2,890	2,100	1,532	1,392	1,810
Therms per square foot of equivalent grate area	6.96	16.45	-	6.73	6.73	7.93

[a] The above capacities are based upon results attainable with generators having an internal diameter of approximately 9 feet; that of the Lurgi generator is 8.85 feet.

[b] B.t.u. per cubic foot, high value 60° F., 30 inches Hg.

Note-Since the initial preparation of this publication, Dr. Hubmann has advised the Bureau of Mines that it is his recollection that results of tests made at Brüx (Most), Czechoslovakia, indicated a much higher production per hour per square foot of equivalent grate area than the 7.93 therms given in column 6 above.

At first it may seem inconsistent that the gas-making capacity of the Lurgi generator, making gas continuously as described, is not appreciably greater than that of a modern water-gas set; the elimination of the cyclic system common to water-gas practice and the use of pressure both favor the Lurgi process. The use of fine coal, the high moisture content of the coal heretofore used, and the thinness of the hot zone (reaction zone of the fuel bed), all tend to influence capacity adversely. The rate at which the gas reactions occur at the relatively low temperatures that usually prevail in most of the fuel bed (below 1,800° F.) in the Lurgi process are not compatible with high rates of flow through the fuel bed. If higher temperatures are employed, conditions are less favorable for the production of CH_4, and more O_2 is required per 1,000 cubic feet of gas made.

Braunkohle Used in Germany

In certain sections of Germany, a technique for making gas has developed that is radically different from that employed in this country, largely for two reasons, viz., (a) the coals available are much like lignite and therefore are ill-suited for use in the ordinary water-gas generator; and (b) the lack of ample supply of petroleum makes it highly desirable that the oil and tar content of their coal be recovered, either before its use in making gas or in the gasification steps.

It was necessary to use a coal, initially containing up to 50 percent of moisture, which does not form coke but which slacks upon being heated. Advantage was taken of the property which the low-grade lignitic fuels have of being more reactive than the higher-grade coals. Thus, the Lurgi process was developed to use a particular fuel under a prescribed set of conditions. A representative composition of the German Braunkohle (brown coal) is as follows:

	As mined	Partly dried	Dry
Moisture....................percent	52.0	10.0	0.0
Volatile matter Fixed carbon... } ....do.	42.1	79.0	87.8
Ash....................do.	5.9	11.0	12.2
	100.0	100.0	100.0
Calorific value..............B.t.u. per lb.	5,120	9,600	10,660
Ash-softening temperature..............°F.	1832 to 2012		
Total sulfur....................percent	1.81	3.4	3.78
Combustible sulfur....................do.	1.06	2.0	2.22
Sulfur in ash....................do.	.75	1.4	1.56
Tar (by Fischer assay)....................do.	6.93	13.0	14.44

To recover as much tar and oil as possible in gasifying the above, it was found to be desirable to remove the gas from the fuel bed at a relatively low temperature (approximately 300° C.), and this can best be accomplished when the fuel charged into the generator contains an appreciable amount of moisture. Coal containing 18 to 25 percent of moisture is preferred to dry coal when gasification is carried on in the Lurgi generator.

Other Reported Data on the Lurgi Gas-making Process

Although other lines of research were directed to high-temperature gasification of coal, even to the slagging-type producer, the Lurgi process was developed along a different line, i.e., gasification at relatively low temperatures was of most concern. The difficulties experienced in the early stages of experiments to make gas with oxygen were largely due to excessively high temperatures and resultant clinker troubles. It was evident that the amount of oxygen used per unit volume of gas made must be reduced to a minimum, even though it was anticipated that the cost of oxygen would be lowered in due time. Furthermore, the low ash-softening temperature of the available coals also dictated operations should be conducted at low temperatures. Two other important factors appear to have been uppermost in the minds of those responsible for the development of the Lurgi process, namely, the conservation and production of oil. In that process, not only were oil and tar recovered, but when operating at about 20 atmospheres pressure the methane formed was sufficient so that the purified gas could be used as city gas without enrichment. Still another important factor is the difference in volumetric ratio of H_2 to CO in the gas made at low temperatures; the latter temperatures favor a higher H_2 to CO ratio and the production of more CO_2. A gas with a high H_2 to CO ratio is desirable for the synthesis of certain liquid fuels.

Experiments with brown coal containing 18 percent of moisture, using 110 cubic feet of O_2 per 1,000 cubic feet of dry, crude gas made, gave results reported as follows:

Gasification at moderate pressure below 10 atmospheres of a lignitic coal of low tar content:

	Raw gas	CO_2-free gas
CO_2 .... percent	28.0	0.0
CO .... do.	16.0	22.2
H_2 .... do.	50.0	69.4
CH_4 .... do.	3.0	4.2
N_2 .... do.	3.0	4.2
	100.0	100.0
O_2 used per 1,000 cubic feet of gas made .... cu.ft.	110	153
B.t.u. per cubic foot of dry gas at 60° F., and 30 inches of Hg., calculated	244.5	340.0
B.t.u. per cubic foot of saturated gas at 60° F., and 30 inches of Hg., calculated	240.2	334.0

It was estimated that the oxygen, costing 2 Pf. per cubic meter (22.6 cents per 1,000 cubic feet), increased the cost of the CO_2-free gas by 3.3 cents per 1,000 cubic feet.

The influence of pressure on the composition of gas made in a Lurgi generator has been discussed, but the data of table 2 are presented to show the compositions of gases, raw and CO_2-free, made at low temperatures when equilibrium conditions prevail.

TABLE 2. - Gasification of carbon at different pressures at 1,340° F. (theoretical values).

Gasifying pressure	1 atmos.	10 atmos.	20 atmos.
Composition of raw gas, volume percent:			
CO_2	11.3	27.5	31.8
CO	49.0	25.8	20.2
H_2	37.0	30.4	25.8
CH_4	2.7	16.3	22.2
	100.0	100.0	100.0
Composition of CO_2-free gas, volume percent:			
CO_2	0.0	0.0	0.0
CO	55.2	35.6	29.7
H_2	41.7	42.0	37.8
CH_4	3.1	22.4	32.5
	100.0	100.0	100.0
High calorific value of the dry raw gas at 60° F. B.t.u. per cu.ft.	308	348	375
High calorific value of the dry CO_2-free gas at 60° F. do.	347	480	550
O_2 used per 1,000 cubic feet of dry CO_2-free gas cu.ft.	164	124	102

Actual tests made on a moderate scale for a number of different fuels gave results as shown in table 3:

TABLE 3. - Results obtained in a small generator with an internal sectional area of approximately 10.765 square feet and using different fuels[a]

Fuel used	Semi-coke (breeze)[b]		Anthracite, 6% vol.[c]	Brown coal (Saxony)[d]		Brown coal[e]
Test number	1	2	3	4	5	6
Absolute pressure........atmospheres	1	18	26	26	30	26
Fuel charged per square foot sectional area per hour..........lb.	22.5	20.5	72.8	106.6	104.5	94.3
Raw gas composition:						
CO_2 H_2S..............percent	25.5	35.2	35.2	31.9	38.2	32.1
Illuminants...............do.	.2	.3	.3	.6	.9	.4
O_2.......................do.	.1	.2	.2	.3	.1	.2
CO.........................do.	21.0	17.0	9.7	17.2	10.9	15.5
H_2.......................do.	51.4	34.0	43.1	36.3	37.2	39.0
CH_4......................do.	1.8	13.3	11.5	13.7	12.7	12.8
	100.0	100.0	100.0	100.0	100.0	100.0
Scrubbed gas composition:						
CO_2 H_2S..............percent	3.0	3.0	3.0	3.0	3.0	3.0
Illuminants...............do.	.3	.4	.4	.8	1.3	.6
O_2.......................do.	.1	.3	.1	.4	.2	.3
CO.........................do.	27.3	25.6	14.5	24.5	17.4	22.1
H_2.......................do.	66.9	50.9	64.7	51.8	58.2	55.7
CH_4......................do.	2.4	19.8	17.3	19.5	19.9	18.3
	100.0	100.0	100.0	100.0	100.0	100.0
Calculated heating value of the scrubbed dry gas, 60° F., 30 inches Hg., ...B.t.u. per cu.ft.	336	457	441	461	473	450

[a] Results according to the German engineer, Otto **Hubmann.**

[b] Tests 1 and 2 were made with "Grudekoks," which is carbonized brown coal.

[c] Test 3 **was** made with a noncoking coal of higher rank than brown coal.

[d] Tests 4 and 5 employed Saxony brown coal.

[e] Test 6 was with German brown coal.

These tests indicated that using a dust-free coal, size 0.12- to 0.31-inch, moderately high gas-making rates could be obtained at 20 or more atmospheres pressure, and that the drop in pressure through the fuel bed was not high, being of the order of 2 inches of water with a bed 9 feet deep.

Results obtained under test conditions on the small generator having an internal diameter of approximately 4 feet, which are said to be "average results", are as follows:

Fuel used, dried and screened brown coal.

Distillation (carbonization) yields:

Tar..	weight percent	10.2
Water of distillation......................	do.	7.4
Water (moisture in coal)...................	do.	27.4
Coke (char)................................	do.	44.9
Gas and remainder..........................	do.	10.1
		100.0

Proximate analysis of coal:

Moisture	percent	27.4
Volatile, plus fixed carbon	do.	67.5
Ash	do.	5.1
		100.0

Elementary analysis of coal:

Carbon	percent	49.0
Hydrogen	do.	3.4
Sulfur (combustible)	do.	0.7
Oxygen and nitrogen	do.	14.4
Ash	do.	5.1
Moisture	do.	27.4
		100.0

Screen analysis (converted from original data, which was given in metric units):

Size

Through 0.315-inch on 0.197-inch	percent	39.2
Through 0.197-inch on 0.079-inch	do.	56.8
Through 0.079-inch on 0.039-inch	do.	2.5
Through 0.039-inch on 0.020-inch	do.	0.7
Through 0.020-inch	do.	0.8
		100.0

Calorific value of the coal:

High value	B.t.u. per lb.	8530
Low value	do.	7910
Coal gasified per 24 hours	lb.	47,390
Coal gasified per hour per square foot of internal sectional area of the generator	lb.	183

Composition of gas made:

		Raw gas	Scrubbed gas
$CO_2 + H_2S$	volume percent	30.6	3.0
Illuminants	do.	0.6	0.7
Oxygen	do.	.1	.1
Carbon monoxide	do.	16.5	23.1
Hydrogen	do.	34.0	47.7
Methane	do.	16.3	22.8
Nitrogen	do.	1.9	2.6
		100.0	100.0
Calorific value, dry gas at 60° F. and 30 inches mercury	B.t.u. per cu.ft.	351	474
Specific gravity, dry gas		0.765	0.463
Hydrogen sulfide, grains per 100 cubic feet		287	0.0

Ammonia, per 100 cubic feet scrubbed gas produced	grains	0.0074
Oxygen used per 1,000 cubic feet of dry scrubbed gas made	cu.ft.	150
Steam used per 1,000 cubic feet of dry scrubbed gas made	lb.	60

Tar recovered, - 72 percent of the total tar content of the coal.

A reported heat balance in gasifying brown coal in the test generator is shown as follows:

Heat balance of pressure gas operation of a small test generator using screened, partly dried, brown coal containing 27 percent moisture

	Percent
Input:	
Heat in the coal	89.9
Heat in the steam	10.1
	100.0
Out:	
Heat of combustion of the scrubbed gas	62.2
Heat of combustion of the tar and benzine	14.3
Combustible matter with the ash	0.4
Phenol in the wash waters	0.9
Steam produced in water jacket	0.6
Sensible heat of the gases and heat lost	16.2
Heat lost in steam superheater ventilation lines	5.4
	100.0

Heat of combustion of the gas, tar, and oil represents 76.5 percent of the heat input as coal and steam. Although the tests were made under conditions not readily obtainable in average plant operation, the results are presented to indicate that under favorable conditions high conversion efficiency may be obtained.

Subsequent to the experiments of Dr. Otto Hubmann in Germany, Dr. Friedrich Danulat of Frankfurt, a representative of the Lurgi Co., reported on the pressure gasification of coal in a Lurgi generator at a time when first-hand data on full-scale operations were available to him; some of the data reported by the latter are presented as follows:

Operations with various coals at 20 atmospheres absolute pressure:

Fuel	Brown coal (Lausitz)	Brown coal (middle Germany)	Hard coal (noncoking coal from the Ruhr)
Composition:			
Moisture, weight percent	27.4	16.9	6.6
Volatile and fixed carbon, do.	67.5	72.5	88.4
Ash, do.	5.1	10.6	5.0
	100.0	100.0	100.0
Tar content, percent by weight	10.2	14.8	0.0
Calorific value, high value, B.t.u. per lb.	8520	9060	13,680
Size, inches	0.08-0.39	0.08-0.39	0.12-0.39
Composition scrubbed, purified gas:			
CO_2, volume percent	3.0	2.3	1.0
Illuminants, do.	0.5	0.9	0.3
O_2, do.	0.1	0.2	0.0
CO, do.	22.8	22.0	27.9
H_2, do.	48.7	50.7	52.4
CH_4, do.	22.6	21.8	16.9
N_2, do.	2.3	2.1	1.5
	100.0	100.0	100.0

Fuel	Brown coal (Lausitz)	Brown coal (middle Germany)	Hard coal (noncoking coal from the Ruhr)
Specific gravity	0.448	0.435	0.410
B.t.u. per cubic foot of dry gas at 60° F. and 30 inches Hg	456	479	437
Oxygen used per 1,000 cubic feet of dry gas ....cu.ft.	150	147	198
Steam used per 1,000 cubic feet of dry gas ....lb.	66	77	83
Tar recovered .... percent of analytical value	72	84.3	0.0
Yield of dry gas (at 60° F., 30 inches Hg.) per ton of 2,000 pounds of coal ....cu.ft.	25,600	22,800	53,100
Coal consumed per 1,000 cubic feet of gas made ....lb.	78.2	87.8	37.8

It is noted that the O_2 consumed in making gas from the relatively high-rank noncoking coal is about 35 percent higher than when gasifying the lower-rank fuels. No doubt the lower reactivity of the high-rank fuel made necessary operation at higher temperatures, which in turn called for a greater amount of O_2. Under these conditions, one would expect the resulting gas to contain somewhat less CH_4 and more CO, and this is shown to be the result obtained.

It is recognized that the differences in moisture contents and volatile matter in the different fuels has a definite bearing on the amount of oxygen consumed per pound of coal gasified. Comparing columns 1, 2, and 3, it is noted that the volumes of gas made per ton of coal gasified are not proportional to the calorific value of the different fuels, but, on the contrary, the gas volume is greater than this ratio for the high-rank low-moisture-content fuel.

Factors Relating to Comparative Costs

Interest centers in the relative cost of ordinary water gas and Lurgi-process gas. Although the major item favoring the Lurgi process is its adaptability to handle fuels unsuitable for use in standard gas-generating sets, the following comparison is made to show some important relationships:

Relative costs of materials used making water gas and Lurgi pressure-process gas

	Ordinary water gas, 1 atmosphere[a]		Lurgi pressure-process gas, 20 atmospheres[a]	
	Per 1,000 cu. ft.	Per therm	Per 1,000 cu. ft.	Per therm
Coke, 40 pounds per 1,000 cubic feet at $6 per ton..............	$0.120	$0.040	-	-
Coal, crushed and screened, 1/8- to 1/2-inch subbituminous quality, 90 lb. at $3 per ton........	-	-	$0.135	$0.030
Oxygen, 145 cubic feet per 1,000 of purified Lurgi gas at 18¢ per 1,000 cubic feet.................	-	-	0.026	0.006
Steam, 40 pounds per 1,000 cubic feet of water gas at 25¢ per 1,000 lb.	0.010	0.003	-	-
Steam, 66 pounds per 1,000 cubic feet of Lurgi gas at 25¢ per 1,000 pounds....................	-	-	0.017	0.004
	0.130	0.043	0.178	0.040
Credits per 1,000 cubic feet and per therm of gas made:				
Tar, 112 pounds per ton of coal at 4¢ per gallon.............	-	-	$0.024	$0.005
Benzine (light oil), 6.31 gal. per ton of coal at 8¢ per gallon.......................	-	-	0.024	0.005
Total credits....................	0.000	0.000	0.048	0.010
Net materials cost, less credits..	0.130	0.043	0.130	0.030

[a] Water gas calorific value = 300 B.t.u. per cubic foot; Lurgi gas, 450 B.t.u.

The gas made in the pressure gasification, as above, is at 20 atmospheres absolute pressure and need not be compressed further for transmission or for use in the Fischer-Tropsch process. Without further treatment, however, it is noted that 1,000 cubic feet of water gas contains 900 cubic feet of $CO + H_2$, whereas the same amount of scrubbed pressure gas contains only 700 cubic feet of $CO + H_2$.

The foregoing costs are not representative of the relative cost of finished gas by the two processes, because other items, such as maintenance, taxes, amortization, labor, relative generator capacities, and other costs, which are not identical in the two cases and cannot be evaluated accurately at this time, are not included. The important consideration is that an appreciable difference in the relative costs of generator fuel and in the credits for byproducts are required, as indicated, to favor the pressure process. In view of the higher calorific value of the pressure-process gas, a more equitable comparison might be the materials costs of carbureted water gas and pressure gas; these costs are compared as follows:

Relative costs of materials used in making carbureted-water gas and Lurgi pressure-process gas, per 1,000 cubic feet

	Ordinary carbureted water gas	Pressure, process gas
Operating pressure.........................atmospheres	1	20
Calorific value....................B.t.u. per cu.ft.	466	466
Coal, 1/8- to 1/2-inch, 90 pounds at $3 per ton.cents	-	13.50
Coke, 30 pounds at $6 per ton.....................do.	9.00	-
Carbureting oil, 2.08 gallons at 6¢ per gallon....do.	12.48	-
Steam (for generator, turbine, booster, etc.) 100 pounds at 25¢ per 1,000 lb. ....do.	2.50	-
Steam (total for pressure gas operations) 66 lb. at 25¢ per 1,000 lb. ....do.	-	1.65
Oxygen, 144 cubic feet at 18¢ per 1,000 cubic feet...do.	-	2.60
Credits:	23.98	17.75
Tar...cents	2.0	2.4
Benzole and light oils........................do.	-	2.4
	2.0	4.8
Total materials, less credits....................cents	21.98	12.95

It will be noted that in the pressure-gas process the light oils are recovered by ordinary condensation on cooling the gas.

A plant for the complete gasification of coal under pressure and purification of the gas includes:

1. An oxygen-producing and compressing plant
2. Gas generator house with generators
3. Steam superheater
4. Condensing equipment
5. Pressure scrubbers
6. Dry purification equipment
7. Gas holder
8. Tanks, reservoirs, and water ponds
9. Light oil-recovery plant
10. General utilities, and
11. Coal- and ash-handling equipment.

In case steam and electrical power cannot be purchased economically "at the plant gate" a power plant is also required. Likewise, if the coal purchased is not sized as delivered, it is necessary that a coal-crushing and screening plant be a part of the whole, and means must be provided for disposing of the fines (dust coal). The fine coal, of course, can be used as boiler fuel for the generation of steam.

Information relating to the cost of such a gas plant and certain other costs under normal conditions for making gas by the pressure process at approximately 20 atmospheres pressure may be gleaned from the data given below, which the author obtained from engineers in Germany experienced in this field:

Basis:

Annual production of purified gas measured dry at 60° F., and 30 inches mercury	cu.ft.	3,720,000,000
Calorific value	B.t.u. per cu.ft.	458
Coal used, proximate analysis:		
Moisture	percent	15.00
Volatile and combustible	do.	75.00
Ash	do.	10.00
		100.00
High calorific value	B.t.u. per pound	7,740
Ash-softening temperature	° C.	1,100
Efficiency of gasification of coal (Including the heat energy of the tar and oil, but excluding heat input as steam)	percent	84.8

The efficiency of conversion of the fuel, not including the heat in the O_2 and steam, is given as follows:

$$\text{Efficiency} = 100\ \frac{[(4{,}300 \text{ cal. per Nm}^3 \text{ of gas})(0.65) + (850 \text{ cal. in tar and oil})]}{4{,}300 \text{ calories per kgm. of coal}}$$

= 84.8 percent.

The figure 0.65 is the number of cubic meters of gas from 1 kgm. of the coal. Calculated in terms of U. S. standard units, the conversion efficiency is:

$$\text{Efficiency} = 100\ \frac{[(458.7 \text{ B.t.u.})(10.97) + (1{,}530 \text{ B.t.u.})]}{7740} = 84.8 \text{ percent}$$

In the latter computation, 458.7 is the B.t.u. per cubic foot of dry gas made from 1 pound of coal; 1,530 B.t.u. is the heat of combustion of the tar and oil made in gasifying 1 pound of coal; and 7,740 is the calorific value of the coal in B.t.u. per pound.

Annual costs:	Reichsmarks	Dollars
Coal used per year, 170,000 short tons at 5.88 Rm., or $2.352 per short ton	1,000,000	400,000
Electric power, purchased at 0.02 Marks or 0.8 cent per kw.-hr.	500,000	200,000
Steam, 154,000 short tons purchased at 2.28 Rm., or $0.912 per short ton	350,000	140,000
Cooling water,a/ 700,000 m^3 (24,717,000 cu.ft.)	35,000	14,000
Repairs, labor	280,000	112,000
Repairs, materials	162,000	64,800
Amortization (12 percent on investment)	780,000	312,000
Total annual costs	3,107,000	1,242,800
Estimated total cost of plant	6,500,000	2,600,000

a/ The total water consumed in actual operations appears to be approximately three times the figure given.

The plant can be operated, it is said, by four shifts of 28 men each, or 112 men per day, but the effective running time is considered to be 7,000 hours per year or 292 days. It is said that these men can handle the oxygen plant and purification equipment, as well as operate the generators. Steam and electric power are considered to be available by purchase "at the gate." On this basis, the cost of the scrubbed gas is given as 3 Pf. per m^3 (32.3 cents per 1,000 cubic feet) without allowing credit for the tar and oil. These cost data were compiled after the actual experience of building and operating a plant. It is interesting to note that the total cost of the plant ($2,600,000) included $676,000, or 26 percent of the total, as the cost of the Linde-Frankl oxygen plant. The oxygen required varies with the nature of the fuel used but averages 15 to 18 percent by volume of the purified gas made at approximately 20 atmospheres pressure. The electric power used for oxygen production included in the above cost data is 0.67 kw.-hr. per cubic meter of dry O_2 at 0° C. and 760 mm. pressure, equivalent to 19 kw.-hr. per 1,000 cubic feet similarly measured.

The foregoing cost data relate to the production of gas having a calorific value of approximately 450 B.t.u. per cubic foot. Calculating the cost to the equivalent of 1,000 cubic feet of 300 B.t.u. gas, the estimated cost would be $\frac{300 \times 32.3}{450}$ cents, or 21.5 cents, without allowing for credits for tar and oil.

In using these estimated costs, it must be kept in mind that in transposing the costs in Reichsmarks to dollars the arbitrary value of 1 Mark equivalent to 40 cents was chosen because it appears to express a proper relationship of values of things bought with the Reichsmark in Germany and the dollar elsewhere. It is believed that an attempt was made in the above estimate to figure costs as close to minimum as possible under the prevailing conditions. Some of the items, such as steam and electric current, cost less in the United States, but certain other items including taxes, insurance, and the like, must be included in applying the data to American conditions.

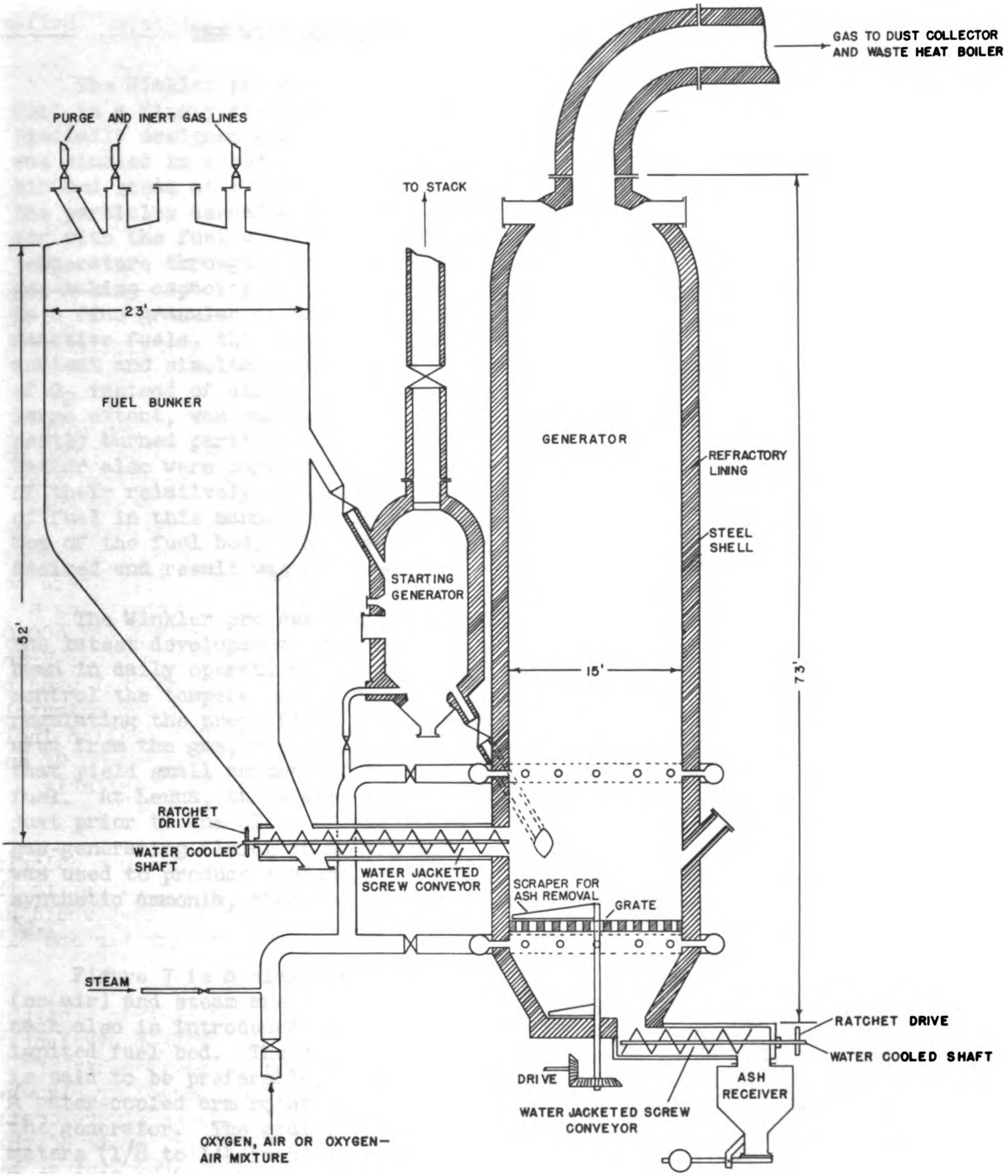

FIGURE 7.- DIAGRAM OF A WINKLER GENERATOR.

THE WINKLER GENERATOR AND GASIFICATION PROCESS

The Winkler process for making gas comprises the gasification of solid fuel in a finely divided state while it is in a fluidized state confined in a specially designed generator. The initial conception was that when a fire was kindled in a bed of fine fuel and it was blasted from beneath with mixed air and steam at a sufficiently high velocity, the mass would be fluidized, the particles assuming ebullient motion, and the reaction of the steam and air with the fuel would be continuous, with considerable equalization of temperature throughout the bed. It was believed that not only could a high gas-making capacity be obtained in this manner, but the ash could be removed in a fine granular or powdered state. It was found that with certain highly reactive fuels, this could be accomplished. The desire to reduce the nitrogen content and simultaneously raise the calorific value of the gas led to the use of O_2 instead of air in admixture with steam. It was found that the ash, to a large extent, was carried along entrained in the gas, and, furthermore, the partly burned particles of fuel still containing considerable combustible matter also were carried out of the generator entrained in the gas by virtue of their relatively small size. Thus, it became necessary, to reduce the loss of fuel in this manner, to introduce O_2 along with steam at a level above the top of the fuel bed. This was an important improvement in the process; the desired end result was obtained.

The Winkler process has been used successfully in Germany at Leuna, where the latest developments were made, and at Zeitz, where large generators had been in daily operation. As in the pressure-gas process, it was necessary to control the temperature of the fuel being gasified, which is accomplished by regulating the proportions of steam and O_2 or steam and air. Tar is not recovered from the gas, nor is it present therein in appreciable amounts. Fuels that yield small amounts of tar only are preferable to other types of solid fuel. At Leuna, there were five Winkler generators, but only two were in use just prior to the close of the European war; one employed air and steam as gas-generating fluids in making power gas, and the other, similarly operated, was used to produce a high nitrogen-content gas for control purposes in making synthetic ammonia, that is, for controlling the amount of N_2 in admixture with H_2.

Figure 7 is a diagrammatic view of a Winkler generator. As shown, oxygen (or air) and steam are introduced beneath the grate at the bottom, and some of each also is introduced at a number of inlets at a common level above the ignited fuel bed. The depth of the fuel bed is 39 to 58 inches, although it is said to be preferable, usually, to maintain the depth at about 39 inches. A water-cooled arm rotating about a central axis helps to discharge ashes from the generator. The grates comprise fire bricks placed on edge a few millimeters (1/8 to 1/4 inch) apart. The upper inlets for steam and O_2 are located 9 feet 10 inches above the grate. The prepared fuel, stored in a reservoir adjacent the generator, is fed into the generator by means of a screw conveyor, which operates continuously.

Kind of Fuel Adapted for Use in a Winkler Generator

Although it is true that fine sizes of solid fuel may be used successfully in a Winkler generator, it does not follow that all solid fuels can be thus gasified. The physical and chemical properties of the fuel used have considerable to do with the results of gasification. Some of these properties are:

(a) Sizes and range in sizes of fuel used.

(b) Softening point of the fuel ash.

(c) Reactivity.

(d) Tar content of the fuel.

(a) Size of fuel. - When maintaining the mass of fuel in a fluidized state in the generator, it is necessary that the velocity of the fluids (gas-making fluids and reaction products) passing into and through the bed be greater than a fixed minimum, which latter is that at which particles begin to settle and separate from the fluidized state. Employing the necessary velocity, there is a tendency for the finer particles to be carried away entrained in the gas, hence a large variation in particle size in the fuel charged should not obtain. The ideal condition would be complete uniformity of particle size. Of course, even with this state the burning of the fuel in gas-making reactions would cause progressive variation in size, and the very small particles would be carried along with the gas stream. In commercial operation of the Winkler process employing carbonized brown coal as fuel, a satisfactory size (the size actually used) was 3 to 4 mm., which is 0.118 to 0.158 inch. Small amounts of fines and coarser particles also are present in the fuel gas as charged into the generator. Even with the exercise of care in preparing the fuel, the ash blown over or entrained in the gas stream contains considerable combustible matter. It appears that the greater the variation in size of the fuel particles in the fuel charged, the greater is the percentage of carbon in the ash. Accordingly, small and uniformly sized particles are preferred for Winkler generator fuel.

(b) Ash-softening temperature. - The particles of fuel in the fluidized state are in ebullient motion, and there is considerable contact or collision of these particles during the gasification process. It is obvious that should they be heated in the generator above the ash-softening temperature, they will adhere to one another and form larger particles. This could result in the formation of clinkers of appreciable size and hinder smoothness of operation. Furthermore, should the particles be heated above the ash-softening temperature, there would be a tendency for them to adhere to the wall of the generator and accumulate there with understandable deleterious results. Accordingly, it is desirable to keep the fuel particles in the fluidized bed in the generator at a temperature 30° to 50° C. below the ash-softening temperature. In some cases this is an important and definite limitation; thus, fuels having high ash-softening temperatures (2,400° to 2,700° F.) should not cause serious troubles from clinker formation, because it is possible to reach a suitable gas-making temperature appreciably below the ash-softening temperature. However, ashes of many fuels soften at 1,900° to 2,100° F. (1,038° to 1,149° C.), and in this range problems arise. The duration of contact of the gas-making fluids is very short at the necessary high rates of flow, and there is the natural tendency for steam to pass through the fuel bed unreacted, and for the CO_2 content of the gas to be excessively high when relatively low temperatures prevail.

(c) Reactivity of the fuel. - In the use of fuels having low ash-softening temperatures, it is desirable that they be reactive in order to promote suitably complete gas reactions. Brown coal, lignite, and subbituminous coals, or, rather, the char resulting from heating them, are highly reactive and therefore suited for use in a Winkler generator. The author believes that serious difficulties may be experienced in using fuels of low ash-softening temperatures that are not very reactive at the lower temperatures, such as a high consumption but low conversion of steam per unit of gas made, poor quality of the gas made, and a high content of carbon in the ash. Progress in the development of this process may alter these conditions; definite and accurate limitations cannot be made at this time because of lack of complete information based upon experience.

(d) Tar content of the fuel. - In a somewhat minor degree, the tar content of the fuel fed to the generator affects results. The fuel in the feeding mechanism becomes heated appreciably before it is discharged into the generator, and hence if considerable amounts of tar are evolved by such preheating, clogging may occur, or resistance to flow may be so great that extra power will be required to propel the charge into the generator.

When a finely divided coal that evolves tar upon being heated is used as generator fuel, there will be a tendency for agglomeration of the particles as the tar is expelled, and it will be difficult to obtain uniform or satisfactory results. Little information is available on this phase of the subject at present.

Some Results of Operation of the Winkler Process

The results given below are based upon operations, as reported, at Zeitz, Germany. The plant is basically a hydrogenation plant, the raw gas being made in Winkler generators. There were three generators, one of which was used as a spare. The inside diameter of each generator was 8.2 feet. The grates comprised fire brick placed on edge but spaced apart 1/8 to 3/8 inch. A water-cooled scraper arm just above the grate rotated slowly during the operation. The depth of the fluidized fuel was 3.3 to 4.9 feet. Oxygen and steam were admitted above the fuel bed as well as beneath it. The internal diameter of each generator in the widest portion above the grate was 8.2 feet; the section area was 52.8 square feet.

Fuel used	Carbonized brown coal known as "Grudekoks."	
Size of fuel fed to generator	inches	0.12-0.16
Generator fuel used per day	short tons	650.2
Composition of the "Grudekoks":		
Carbon	weight percent	62.0
Hydrogen	do.	2.0
Sulfur	do.	5.8
O_2, N_2, and ash	do.	30.2
		100.0
Softening temperature of the ash	° C.	1,000-1,100
Calorific value	B.t.u. per pound	10,190
Raw gas made daily with two generators, dry at 60° F., and 30 inches Hg	cubic feet	27,656,000
Raw gas made daily with two generators, saturated at 60° F., and 30 inches Hg	do.	28,145,000
Generator fuel used per 1,000 cubic feet of raw dry gas	pounds	47.04
Generator fuel used per 1,000 cubic feet of raw saturated gas	do.	46.15
Steam used per day at 2.5 atmospheres pressure:		
To two generators (process)	short tons	402.3
Total	do.	483.8
Total per 1,000 cubic feet of dry gas at 60° F., and 30 inches Hg	pounds	35.0
Total per 1,000 cubic feet of gas saturated at 60° F., and 30 inches Hg	do.	34.4
Generated, per 1,000 cubic feet of dry gas at 60° F., and 30 inches Hg	do.	42.5
Oxygen used (basis pure O_2):		
Daily supply to two generators, dry at 60° F., and 30 inches Hg	cubic feet	6,721,000
Dry O_2 per 1,000 cubic feet of raw dry gas made	do.	243
Composition of raw gas:		
$CO_2 + H_2S$[a]	percent by volume	24.4
CO	do.	29.1
H_2	do.	44.2
CH_4	do.	0.7
N_2	do.	1.6
		100.0
Calculated high heating value, dry at 60° F., 30 inches Hg	B.t.u. per cubic foot	252
Calculated high heating value, saturated at 60° F., 30 inches Hg	do.	248
Total dust removed from the gas by the dust separators per day	short tons	299.2
(About 80 to 85 percent of this dust was removed in the multiclone separators)		

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[a] The H_2S content was 1.3 percent, leaving 23.1 percent of CO_2.

Composition of the dust:		
Carbon	percent by weight	54.01
Hydrogen	do.	0.89
Ash	do.	45.10
		100.00
Calculated calorific value	B.t.u. per pound	8,200
Composition of the ash collected at base of generator:		
Carbon	percent by weight	25.8
Hydrogen	do.	0.0
Residue	do.	74.2
		100.0
Calculated calorific value	B.t.u. per pound	3,650
Total carbon (combined) in the gas as CO_2, CO, and CH_4, per 1,000 cubic feet of dry gas, computed	pounds	16.80
Actual carbon in the fuel used per 1,000 cubic feet of dry gas, according to the fuel analysis	do.	29.16
Carbon in the dust, per 1,000 cubic feet dry gas	pounds	11.70
Carbon in ash and not accounted for above	do.	0.66
Steam generated (per 1,000 cubic feet of dry gas) at 18 atmospheres pressure	do.	42.5

Calculations based upon the above data but computed with reference to the dry gas free from CO_2 and H_2S, herein designated as "rich gas":

Rich gas composition:		
CO_2	percent by volume	0.0
CO	do.	38.5
H_2	do.	58.5
CH_4	do.	0.9
N_2	do.	2.1
		100.0
Specific gravity		0.438
Calorific value of the dry rich gas	B.t.u. per cubic foot.	324
Rich gas made per day (equivalent)	cubic feet	20,908,000
Materials used and yields per 1,000 cubic feet of dry rich gas as above:		
Process steam	pounds	38.7
Other steam	do.	7.8
Total steam	do.	46.5
Generator fuel	do.	62.2
Oxygen (basis pure dry O_2)	cubic feet	321
Steam generated at 18 atmospheres pressure	pounds	56.2
Rich gas (324 B.t.u.) made per square foot of sectional area of generator per hour, dry gas basis	cubic feet	8,250

Miscellaneous Notes on Operation at Zeitz

Of the total O_2 and steam supplied to the generator, 90 percent of each was introduced beneath the grate, and the remainder was introduced 6.5 feet above the fuel bed. Although it was stated that the generators were not operated at capacity because it was found that erosion occurred in the waste-heat boiler at maximum capacity, and hence lower linear velocities were maintained in the gas stream passing through the heat exchanger to protect it, it is noted that the blown-over fuel, called dust, is a rather high percentage of the total fuel used, hence for all practical purposes it appears that the production given above is close to maximum rate of make. Sufficient information is not available at this time to make a more positive statement as to capacity. The limits of capacity reported are: Minimum 335,000 and maximum 744,000 cubic feet of dry gas per hour measured at 60° F. and 30 inches of mercury pressure. The latter figures correspond to 6,340 to 14,050 cubic feet of gas per hour per square foot of generator sectional area.

The gas from the generators passes through waste heat boilers, dust separators, coolers, and water scrubbers. Gas entering the dust separators is said to contain 17.8 pounds of dust per 1,000 cubic feet of gas; leaving the separators it contains 3.56 pounds; at the outlet of the cooler-scrubbers it contains 1.9 avoirdupois ounces; and at the outlet of the Thiesen scrubbers the dust content of the gas is 1.2 to 1.6 grains per 1,000 cubic feet. The water used for scrubbing the gas absorbs considerable H_2S and CO_2, and these gases are expelled by air blowing before the water is conducted to a settling pond.

The dust collected, which is approximately half carbon, is used as powdered coal for steam generation. This is done usually without grinding, although extra pulverization was practiced for awhile. Dust particles recovered for fuel use are 0.1 to 0.5 mm. (0.004 to 0.020 inch) in size and are adaptable for use as powdered fuel in spite of the high ash content, largely because they are very reactive; this applies to the dust made when gasifying such fuel as "Grudekoks," as described above. Besides the dust carried overhead in the gas, there is approximately 1.89 pounds of ash, removed in a fine granular form, per 1,000 cubic feet of dry raw gas made.

Operation of Winkler Process at Leuna, Germany

At the chemical plant (Merceberg Ammoniakwerke) at Leuna, there were five Winkler generators - four large and one small one. Considerable development work was done at Leuna on this process. The generators, initially designed for gasification with mixtures of air and steam, were subsequently used with mixtures of O_2 and steam, substantially as described in the foregoing.

The large generators had an internal diameter of approximately 18.0 feet and corresponding sectional area of 255 square feet and a rated hourly capacity of approximately 2,676,000 cubic feet of raw dry gas measured at 60° F. and 30 inches of mercury pressure. This is equivalent to 10,494 cubic feet of gas per square foot of sectional area per hour. The small generator had an internal sectional area and capacity half that of the large generators. These generators were operated in much the same manner as the generators at Zeitz. The steam-oxygen mixture introduced below the grate was 40 to 50 percent O_2 and 60 to 50 percent steam (percent by volume), whereas at a level 10 feet above the grate an O_2-steam mixture was introduced comprising 80 percent O_2 and 20 percent steam. This is different from the procedure at Zeitz. The linear velocity of the gases in the generator was said to be approximately 9.84 feet per second at the prevailing temperature. Another figure relating to the limits of generator capacity was given as 3,100 to 9,315 cubic feet per hour per square foot of sectional area, the gas volumes being corrected to 60° F. dry at 30 inches of mercury.

An example of operating results obtained with the small generator is as follows:

Raw gas made per hour, dry and at 60° F., 30 inches Hg.	cubic feet	1,338,000
Fuel used		carbonized brown coal.
Size of the fuel chiefly used (but ranging from 0.118 to 0.394 inches)	inches	0.197
Gas made per square foot of internal sectional area of generator, dry gas at 60° F., 30 inches Hg	cubic feet	10,500
Composition of the raw gas:		
CO_2	percent by volume	20.0
CO	do.	38.0
H_2	do.	40.0
CH_4	do.	1.5
N_2	do.	0.5
		100.0
Calculated high heating value dry gas, 60° F. and 30 inches Hg	B.t.u. per cubic foot	268
Calculated high heating value saturated gas, 60° F. and 30 inches Hg	do.	263
Specific gravity dry raw gas		0.714
Drop in pressure through 1 meter (39 inches) depth of fluidized fuel in generator	inches of water	19.5
O_2 used (pure dry O_2) per 1,000 cubic feet of dry raw gas	cubic feet	250
Total steam used per 1,000 cubic feet of dry raw gas	pounds	19
Temperature in fluidized bed of solid fuel	° F.	1652
Temperature in zone above fuel bed	° F.	2012
Coal used per 1,000 cubic feet of dry gas made, measured at 60° F. and 30 inches Hg	pounds	33

Variation in composition of gas with variations in steam-oxygen ratio and other factors:

CO_2	percent	20.0	to	25.0
CO	do.	38.0	to	28.0
H_2	do.	40.0	to	44.5
CH_4	do.	1.5	to	2.0
N_2	do.	0.5	to	0.5
		100.0		100.0

Total O_2 used ranged from 240 to 300 cubic feet per 1,000 cubic feet of raw gas made.

Total O_2 used per 1,000 cubic feet of CO_2-free gas was 320 to 375 cubic feet.

Notes on the Use of Air Instead of Oxygen in Making Gas in a Winkler Generator

The Winkler generator was initially designed for use with air and steam in making producer gas and was in operation for that purpose until rather recently, making power gas in Germany. When the results making the latter gas are compared with those using O_2, the difference is at first somewhat surprising. The calorific value of the raw producer gas is about 45 percent of the value of the raw gas made using O_2, and the volume made per unit of time using air is 40 percent of that made with O_2. Thus, the thermal output per hour is $\frac{40 \times 45}{100}$, or 18 percent of that made with O_2. In other words, the use of O_2 increases the output of heat energy as combustible gas 5.5-fold. The composition of the producer gas made by blasting with air, along with the required steam, is or may be much the same as ordinary producer gas, although there is a tendency for the CO_2 content to be high and the H_2 low. As in the instances described above, the reactivity of the fuel used has important bearing on the results attained.

It is noteworthy that the Winkler process is used with satisfaction in Germany in making gas for the hydrogenation of tar and for generating power gas for use in internal-combustion engines. Although the process has not yet been developed to the stage wherein all types of solid fuel can be used, it definitely can be used with the reactive solid fuels that are available in the United States.

In figure 8 are shown comparatively the costs of gas-making materials for the Winkler and water-gas processes. The line representing costs for the Winkler process is based upon gas having the same calorific value as water gas, namely, 300 B.t.u. per cubic foot. In this comparison no credit is allowed for the blown-over fuel in making calculations of costs of materials used in generating Winkler gas. With allowance for such a credit, the cost line for the latter gas would be more favorably located in figure 8. The net amount of steam consumed in making water gas is considered to be 50 pounds per 1,000 cubic feet of gas, and this includes the steam for generating gas and for operating air blowers when waste heat economizers are employed. In certain sections of the country where carbonized fuel suitable for use in a Winkler gas generator conceivably might be obtainable at $2.50 per ton, good coke for generating water gas is not obtainable at present at $6 per ton. Under such conditions, other factors remaining the same, there would be a marked saving in making synthesis gas in a Winkler instead of a water-gas generator when the cost of oxygen is 10 cents per 1,000 cubic feet.

THE SLAGGING-TYPE GAS PRODUCER

In times past, various engineers engaged in the manufacture of combustible gas in this county have expressed interest in the production of gas in a slagging-type gas producer. Experimental work in this field is costly and perhaps this is one reason why it has been limited. Considerable work was done on a large scale at the ammonia works at Leuna. There were six generators of this type in the latter plant, one was known as a "Pintsch generator" and the others were built by the "I.G." and were thus designated. A sectional drawing of one of the latter is shown in figure 9.

In the initial attempts to gasify solid fuel, including the step of slagging the ash, fuels of low ash-softening temperatures were selected, and air was used as the chief gas-making fluid. It was found that this operation could be successful, but that it was extremely sensitive to variations in the ash-softening temperature, amount of ash in the fuel used, and the rate of making

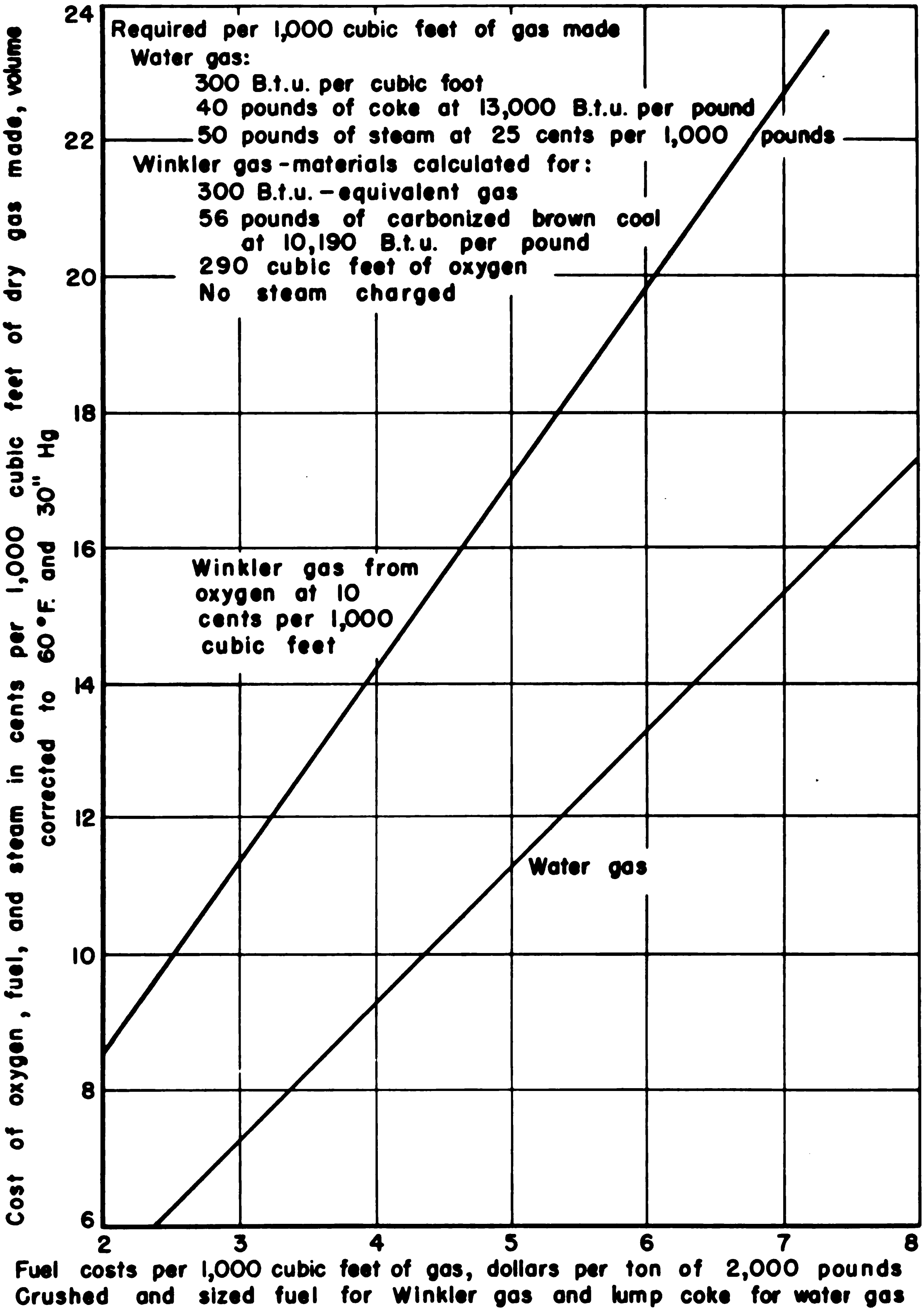

Figure 8.- Comparative costs of materials required in making ordinary water gas and Winkler gas with solid fuel costing $ 2 to $ 8 per ton.

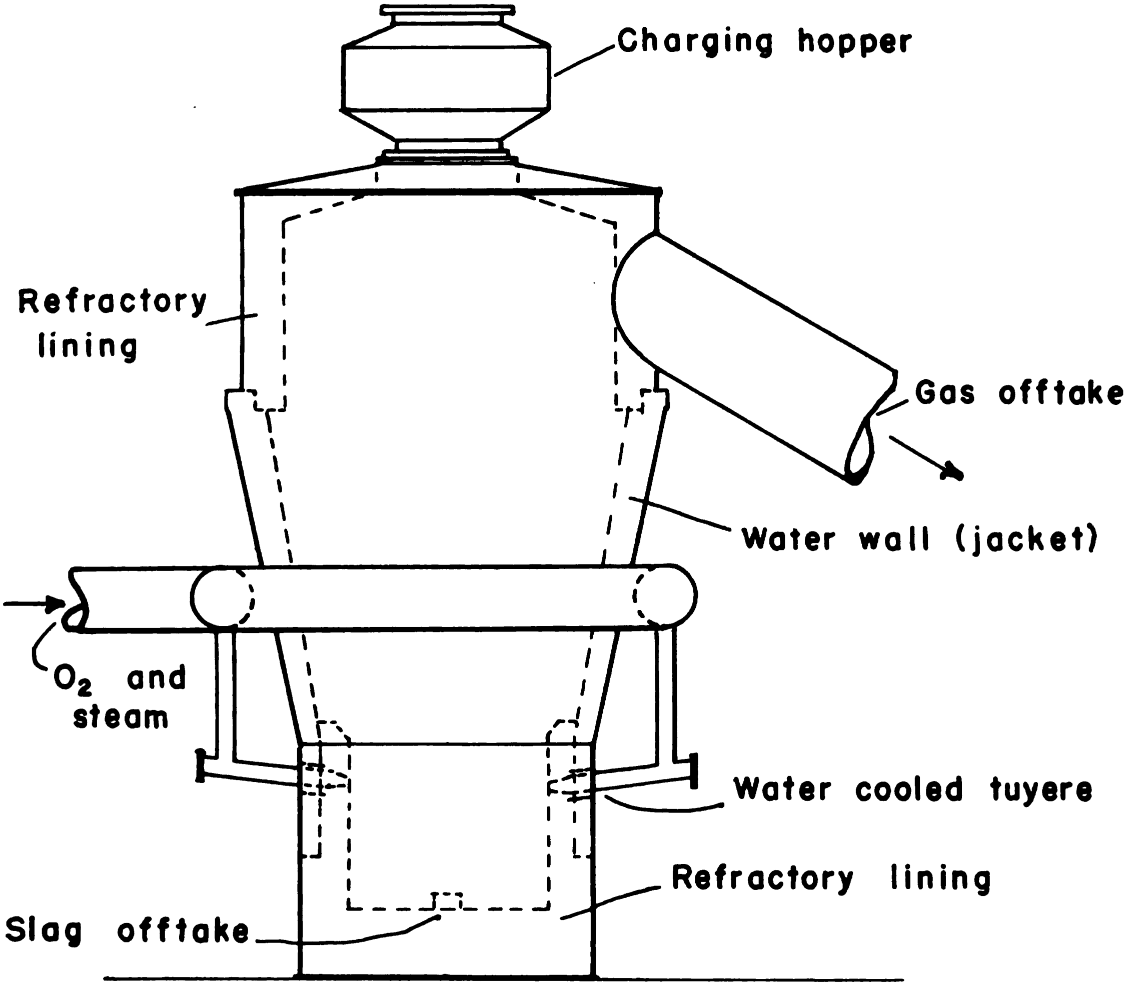

Figure 9.- Diagram of a slagging-type gas producer.

gas, temperature and moisture content of the air and other variables; the danger of serious trouble from freezing was ever present. Quite satisfactory results are attainable when O_2 instead of air is used along with a controlled amount of steam. The generator as at present developed has an internal diameter of 9.87 feet at the tuyeres and a corresponding sectional area of 76.5 square feet. Experience has shown that a complete refractory lining is not required, although as initially built the generator was not only completely lined but steam-jacketed as well.

In the operation of the generator, a fuel-bed depth of about 11.5 feet was maintained. It is, of course, necessary that the composition of the ash be such that it will readily flow as a liquid at the operating temperature. To provide this condition, it is common practice in this particular case to introduce lime into the generator along with the fuel and also to recirculate some of the crushed slag previously withdrawn from the generator. The amounts of lime and slag thus used will vary with different fuels, but in this instance the amount of lime used (introduced as calcium carbonate) was 3 percent of the fuel, and the recirculated slag amounted, with some variation, to as much as 20 percent of the total fuel used. The fuel normally charged to the generator was high-grade furnace coke, sized 1-1/2 inches and larger, free of fines. With this fuel, the capacity of the generator was 468,500 to 502,000 cubic feet of gas per hour, measured dry at 30 inches of mercury and 60° F., and this is equivalent to 6,140 to 6,570 cubic feet per hour per square foot of sectional area at the tuyeres. Thus, one generator of 9.87 feet internal diameter (at tuyeres) has a daily capacity of 11,244,000 to 12,048,000 cubic feet of gas. A representative composition of the generator gas is as follows:

Composition of producer gas from coke:

CO_2	percent by volume	3.5
CO	do.	68.0
H_2	do.	28.0
N_2	do.	0.5
		100.0
Specific gravity		0.735
Calculated high heating value dry gas at 60° F. and 30 inches Hg	B.t.u. per cubic foot	311
Calculated high heating value saturated gas at 60° F. and 30 inches Hg	do.	306

In producing this gas, the ignited bed of coke confined in the generator is blasted with a mixture of steam and O_2 in proportions adapted to provide a temperature of 1,700° C. in the fuel bed adjacent the tuyeres. Using furnace coke as fuel, the proportions of steam and O_2 employed are:

O_2	percent by volume	35	to 40
Steam	do.	65	to 60
		100	100

The materials used per 1,000 cubic feet of gas made, measured dry at 60° F., and 30 inches of mercury, were:

Oxygen	cubic feet	250
Steam	cubic feet	470
Coke	pounds	26.7
Actual carbon combined as CO and CO_2 in 1,000 cubic feet of the gas	pounds	22.72
O_2 in the gas, calculated from the analysis per 1,000 cubic feet of gas	cubic feet	248
(Coke used was furnace grade, larger than 1-1/2 inches)		
Interval between slag draw-off periods	minutes	20
Temperature of gas at generator offtake	° C.	400

The gas thus made was found to be quite satisfactory as fuel and power gas, but the belief was expressed that it was essential for best results to use high-grade coke over 1-1/2 inches in size, free of fines. It was reported that the use of the water jacket as initially planned was not necessary; the preferred method of cooling of the generator wall was to spray water against the outside of the inner wall.

In one experimental run, carbon dioxide was used instead of steam, along with the O_2 supplied to the generator, as a temperature-controlling medium. This operation was successful, and the resulting gas contained 94 percent of carbon monoxide. Approximately the same amount of O_2 is required per 1,000 cubic feet of this gas as when making gas from steam-oxygen mixtures. On this basis, it follows that out of every 1,000 cubic feet of gas made, about 500 feet of carbon monoxide comes from reaction of O_2 with carbon, and about 400 cubic feet of it comes from the reaction of carbon dioxide with carbon. Accordingly, the materials required per 1,000 cubic feet of this gas are approximately 250 cubic feet of O_2, 260 cubic feet of CO_2, and about the same amount of coke as above (26.7 pounds), varying somewhat with the inlet temperatures of the CO_2 and steam. . . . .

In making gas by either of the foregoing procedures, slagging the ash and withdrawing it as a liquid, the carbon-gasification efficiency is high. All of the carbon of the fuel used appears in the gas, which gas contains only a small amount of CO_2 or other inert matter. It is noteworthy that although the gas is designated "producer gas," it has a high calorific value and is in effect much the same as water gas, the difference being in its lower H_2 to CO ratio, which difference is occasioned by the use of O_2 in gasification.

One interesting experiment was performed with satisfactory results that appreciably increased the production of hydrogen at the Ammoniawerke at Leuna. The water-gas generators used for making gas for the synthesis of ammonia were modified Pintsch generators with automatic grates; their combined capacity was too small to satisfy the demands for gas. The capacity was increased by forcing the maximum amounts of air and steam into the fuel bed during the respective portions of the cycle, meanwhile operating the automatic grate at a greater rate for the purpose of keeping the fuel bed "loose and open," so that the amounts of steam and air used are appreciably greater than when the grate is in normal operation. The triple effects of these changes were:

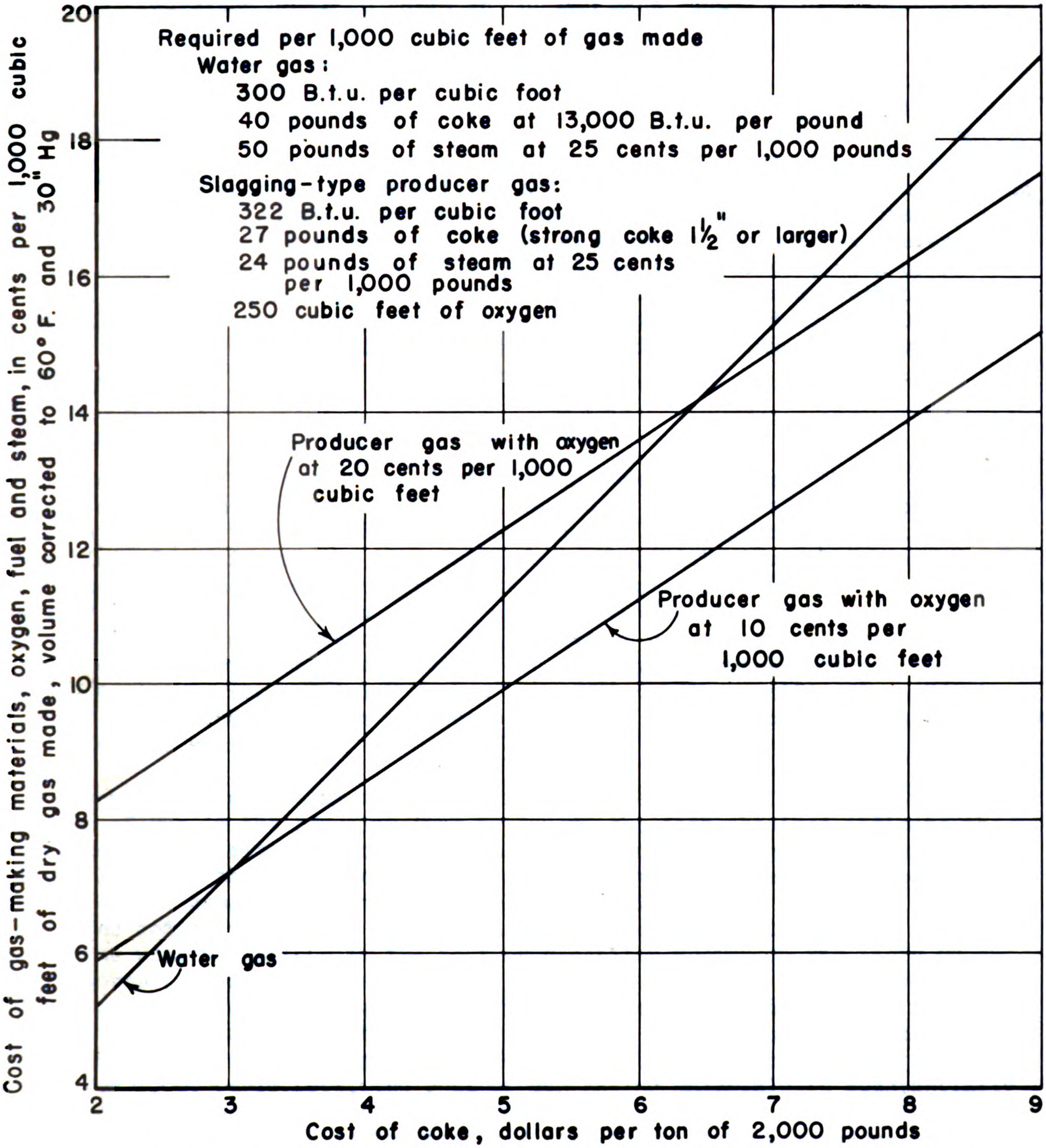

Figure 10.– Comparitive costs of materials required in making ordinary water gas and slagging-type producer gas.

(a) Increased production of water gas,

(b) Increased H_2 to CO ratio in the gas made, and

(c) Increased amount of carbon in the ash.

The ash comprised to a large extent pieces of coke cemented into agglomerates with mineral matter that had been partly fused. The actual combustible matter (carbon) in the agglomerates was 50 to 55 percent. The latter were not discarded but were washed to remove fines and dust and were then used as charging stock to the slagging gas producers. With this fuel it was not necessary to introduce additional (recirculated) slag, although at times it was necessary to add some lime to the charge. The gas made in the producer, when operated in this manner, was equally as satisfactory as that made from fresh coke; however, the rate of make, or gas-making capacity, was lowered to 340,000 cubic feet per hour, a decrease of 28.5 to 33 percent from maximum capacity with lump coke.

Remarks

The value of this process of making gas under conditions in the United States depends on a number of factors, including the cost of O_2. The high gas-making capacity relative to that obtained in other processes making the same kind of gas favors the slagging-type process. The fact that the operation is continuous also favors the latter. Against these advantages must be weighed the cost of the required O_2, cost of recirculating slag, and difference in the cost of generator fuel above that of generator fuel used in other processes. The progress made thus far in Germany indicates that screened fuel having a minimum size of 1-1/2 inches is required. The gasification efficiency is high, as indicated by the gas composition and the fuel consumption per 1,000 cubic feet of gas made.

Even though operating costs were not obtained with reference to the production of gas in the slagging-type producer, the data obtained indicate the usefulness and limitations of the latter producer in making synthesis gas. Figure 10 shows the effect of changes in the costs of oxygen and coke upon the total cost of gas-making materials per 1,000 cubic feet of gas made; it also indicates comparatively the changes in the cost of materials used in making water gas with variations in the cost of generator fuel. On the basis of these costs (gas-making materials only), the use of oxygen at a net cost of 20 cents per 1,000 cubic feet, making the producer gas as described, is not economical, compared with the ordinary water-gas process, until the cost of coke reaches $7.50 or more per ton. However, with a net cost of oxygen at 10 cents per 1,000 cubic feet, the cost of gas-making materials is substantially the same for both gases (producer and water gas) when coke costs $3.20 per ton. Thus, the economy in making the producer gas with oxygen is greater, as the net cost of oxygen decreases and the cost of coke increases. Accurate total or operating costs of making producer gas with oxygen are not available to the author, but it seems reasonable to assume that the benefits derived from high gas-making capacities are not entirely neutralized by other costs characteristic of this process; hence, with the prevailing cost of coke, it may be advantageous to make gas in a slagging-type producer with oxygen instead of by the standard water-gas process when the net cost of oxygen decreases to 10 cents or less per 1,000 cubic feet.

The foregoing comparison was made on the basis of the production of a unit volume of gas without consideration of differences in composition of the gases made or their relative usefulness in producing synthesis gas or hydrogen. The H_2 to CO volumetric ratio in water gas usually is 1.25, whereas in the producer gas this ratio is 0.41. Accordingly the extra cost of conversion to the desired gas must be considered before any advantage in the production of gas by the use of oxygen in a slagging-type producer can be proclaimed. When hydrogen is the end product sought it will be necessary to treat all of the latter gas whereby the 68 percent of carbon monoxide normally present therein is converted by the "shift reaction" to an equivalent amount of hydrogen. This reaction ($CO + H_2O = CO_2 + H_2$) is conducted at 400° to 450° C. in the presence of an iron-oxide catalyst and requires an excessive amount of steam. If, on the other hand, the gas sought is synthesis gas having a ratio H_2 to CO equal to 2, only a portion of the producer gas need be treated in this manner, namely, about 60 percent when allowance is made for incompleteness of the reaction with such a high initial carbon monoxide content. In each case the carbon dioxide formed is scrubbed out of the resulting gas.

Cost of Oxygen

Of recent years the subject "cost of producing oxygen" has been of increasing interest to gas engineers because the natural belief exists that the cost will progressively decrease with time, which is usual for other products of manufacture when demand warrants their use. The cost of making O_2 has already decreased over the past 10 years, and there is little doubt that it will be produced in the future at a lower cost. Using high-priced fuels, the cost of O_2 may be vitally important, but in gasifying low-cost fuels a greater charge for the required O_2 may not be prohibitive. In other words, when one can substitute a low-cost fuel for an expensive one in making gas, the cost of using O_2 with the former may be more than offset by the savings in the cost of fuel.

The cost of O_2 as made in a large plant in Germany operated in conjunction with another plant that consumes O_2, as given to the author by the head of a large construction company interested in erecting oxygen plants, is 2.3 to 2.5 Pf. per normal cubic meter, which is equivalent to 24.7 to 26.9 cents per thousand cubic feet of dry O_2 measured at 60° F., and 30 inches mercury pressure; this equivalence is based upon one Mark being equal to 40 cents. Electric power cost was 0.6- to 0.7-cent per kw.-hr. On this basis, and taking 18 kw.-hr. as the power consumption per 1,000 cubic feet of O_2 produced, the cost of the electric current required was equivalent to 10.8 to 12.6 cents per 1,000 cubic feet of O_2. Obviously, the cost of O_2 would be reduced by about 3.6 cents per 1,000 cubic feet if the cost of power were reduced to 0.4 cent per kw.-hr., making the over-all cost 21.1 cents. To verify this cost estimate, data were obtained from a large chemical plant operating a large Linde-Frankl O_2 plant as a part of the whole works. In this case the cost of O_2 was said to be 1 Pf. per normal cubic meter (19.3 cents per 1,000 cubic feet) when

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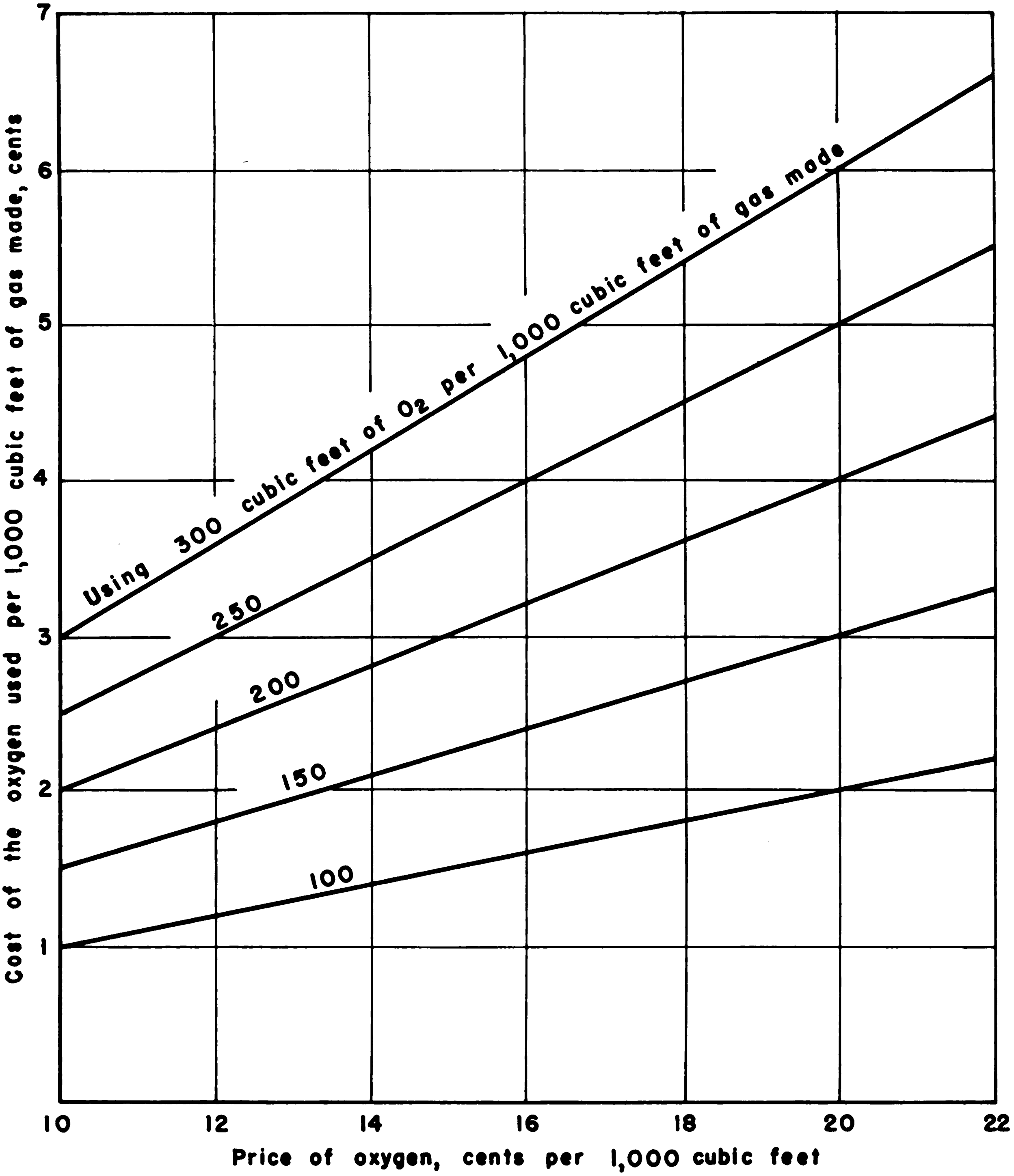

Figure 11.– Cost of the oxygen used in making gas, with variously priced oxygen, using 100 to 300 cubic feet of it per 1,000 cubic feet of gas made.

electric power cost was 0.4 cent per kw.-hr. Although this is a reasonably accurate estimate, it was stated by an operator at the chemical plant that the cost of O_2 could be divided as follows:

	Percent of total cost
Electric power	60
Amortization	30
Other costs	10
	100

If this "break up" of cost is correct, and O_2 costs 19.3 cents per 1,000 cubic feet, the cost of power would be $\frac{60}{100} \times 19.3$, or 11.58 cents, and the amount of power used accordingly would be $11.58 \div 0.4 = 28.95$ kw.-hr. per 1,000 cubic feet of O_2 produced. This is at variance with the above estimate. Other checks on the cost of O_2 lead to the conclusion that whereas the cost in previous years in Germany was stated to have been 4 to 5 Pf. per normal cubic meter (43 to 53.6 cents per 1,000 cubic feet), improvements made in the process of recovering O_2 from air have lowered the cost materially, so that in the combination of an oxygen plant with a manufacturing plant consuming O_2 the cost is in the approximate range 19 to 24 cents per 1,000 cubic feet. The prospects are that the cost will be lowered further when application is made to industry in the United States.

In all gas-making processes in which O_2 is substituted for air as a gas-generating fluid, the cost of the O_2 consumed must at least be equaled by economies that might be made by virtue of such substitution. In other words, the cost of the fuel used, labor, or other items contributing to the total cost of gas must decrease when air is replaced by O_2. Figure 11 indicates what this economy must be; the figure shows the cost of O_2 per 1,000 cubic feet of gas made for variously priced O_2 and for varying O_2 requirements. The higher the cost per 1,000 cubic feet of O_2 the greater must be the economies neutralizing this cost.

SUMMARY AND CONCLUSIONS

1. Three gas-making processes have been discussed, each of which employs free oxygen as a gas-making fluid; they differ from those in common use in this country.

2. Two of these, the Winkler and the Lurgi pressure gasification process, are unique, in that they use generator fuel in a finely divided state. They apparently have been developed as a means of gasifying certain solid fuels readily available in parts of Germany where other gas-making fuels were scarce. The conditions for gasification have been discussed... The use of oxygen in these two processes has made practicable the gasification of solid fuel that cannot be utilized in ordinary gas generators. It is believed that the Winkler process as now developed and the Lurgi process with some improvement or in a modified form may be used effectively under certain conditions and with particular fuels in this country; this is especially true when the costs of fuel and oxygen are very low.

3. The other process referred to above employs the slagging-type gas-producer principles. The gas thus made differs from ordinary producer gas; its calorific value is higher, and its composition is different from that of the latter gas. Mixtures of oxygen and steam are used as gas-making fluids, and they are so proportioned that a temperature suitable for slagging the ash is maintained in the fuel bed. Slag is withdrawn at intervals of 20 minutes. Normally the fuel used was furnace coke freed from fines and sized by screening 1-1/2 inch and larger. Lime was added to the fuel charged, and required amounts of slag were recirculated (the cooled, crushed slag was recirculated). In a particular case, the lime used amounted to 3 percent of the fuel charged, whereas the amount of slag recirculated was about 20 percent of the total fuel charged.

4. Some operating data relative to the three processes are presented and discussed; they are summarized in table 4 for the purpose of comparison, as follows:

TABLE 4. - Operating data for Winkler, Lurgi, and slagging-type gas generators

	Winkler continuous water-gas process	Lurgi (20 atmospheres pressure) water-gas process[a]	"Slagging" producer-gas process
Fuel used	Carbonized brown coal	Partly dried brown coal (22% water)	Furnace coke
Size of fuel used...inches	0.12 to 0.40	0.12 to 0.40	1-1/2 and larger
Fuel used in generator, pounds:			
Per M. cu. ft.[b] of raw gas	47.04	67.8	26.7
Per M. cu. ft.[b] of gas, free of H_2S and CO_2	62.15	102.0	27.7
Per 300,000[c] B.t.u. in the gas.	59.36	69.6	25.8
Per M. cu. ft.[b] of purified gas (9.1% CO_2)	-	93.6	-
Oxygen supplied to the generator, cu.ft.:			
Per M. cu. ft.[b] of raw gas	243	106.6	250
Per M. cu. ft.[b] of CO_2-free and H_2S-free gas	321	160.8	259
Per 300,000[c] B.t.u. in the gas	307	100.7	241
Per M. cu. ft.[b] of purified gas (9.1% CO_2)	-	147	-
Steam supplied to the generator, pounds:			
Per M. cu. ft.[b] of raw gas	29.1	63.2	22.4 (470 cu.ft.)
Per M. cu. ft.[b] of gas free of H_2S and CO_2	39.5[d]	95.3	23.2
Per 300,000[c] B.t.u. in the gas	37.7	59.7	21.6
Per M. cu. ft.[b] of purified gas (9.1% CO_2)	-	87.2	-

TABLE 4. - Operating data for Winkler, Lurgi, and slagging-type gas generators-Continued

	Winkler continuous water-gas process	Lurgi (20 atmospheres pressure) water-gas process[a]	"Slagging" producer-gas process
Gas made per square foot of generator area (horizontal cross section) per hour, cu. ft.:			
Raw gas[b]	10,500	1,990	6,350[e]
Gas free of H_2S and CO_2	7,950	1,320	6,230
Therms (100,000 B.t.u.)	24.96	6.3	19.74
Purified gas (9.1% CO_2)[b]	-	1440	-
Composition of raw gas, percent:			
H_2S	1.2	1.6	-
CO_2	23.1	32.1	3.5
Illuminants	-	0.7	-
CO	29.1	12.1	68.0
O_2	0.0	0.2	0.0
H_2	44.2	37.5	28.0
CH_4	0.8	14.5	0.0
N_2	1.6	1.3	0.5
	100.0	100.0	100.0
Specific gravity of dry gas	-	0.753	0.735
Calorific value of dry gas, B.t.u. per cubic foot[b]	253	333	311
Composition of purified gas, percent:			
CO_2	0.0	9.1	0.0
Illuminants	0.0	0.6	0.0
CO	38.4	16.7	70.5
O_2	0.0	0.2	0.0
H_2	58.4	52.3	29.0
CH_4	1.1	20.0	0.0
N_2	2.1	1.1	0.5
	100.0	100.0	100.0
Specific gravity of purified dry gas	0.438	0.477	0.707
Calorific value of dry purified gas, B.t.u. per cubic foot[b]	314	438	322

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[a] The figures in this column are based upon actual operating results over a period of one month in early 1945. It was stated that the amounts of steam and solid fuel used were excessive during this period because of interruptions due to the war. Other reported results indicate that the fuel and steam used might be 75 to 85 pounds of 7,500 to 8,000 B.t.u. coal and about 80 pounds of total steam per 1,000 cubic feet of purified gas made.

[b] Measured at 60° F. and 30 inches Hg.

[c] This unit of comparison is chosen because 300,000 B.t.u. represents the heat of combustion of 1,000 cubic feet of water gas measured at 60° F. and 30 inches Hg.

[d] The amount of steam used will vary with the rank and reactivity of the fuel used; at the Leuna plant an appreciably smaller amount of steam was used.

[e] The internal diameter of the generator at the tuyeres was 9.84 feet.

5. In the Winkler and Lurgi processes, the reactivity of the fuel employed is an important factor. These processes are adapted for use in gasifying fuels at temperatures below their ash-softening points, and therefore a highly reactive fuel is desired and in some cases may be essential.

6. In the Lurgi process the methane content of the gas increases with pressure; at 20 atmospheres pressure and with a reactive fuel, operating at 1,000° C. in the hot zone, the methane content of the gas is substantially as shown in table 4. Other factors remaining the same, the use of appreciably higher temperatures causes a reduction of the methane content. The methane produced in this process is formed at temperatures below that prevailing in the hot zone and in the upper portion of the fuel bed. The temperature in the hot zone is kept below the ash-softening temperature. Temperatures favorable to the formation of methane have been discussed.

APPENDIX

Manufacture of City Gas in Conjunction With the Production of Synthetic Liquid Hydrocarbons. (Plant Under Construction at Leipzig.)

At Leipzig, Germany, city gas was manufactured by standard procedures, and both coke-oven gas and water gas were produced. However, during the late stage of World War II, plans were made for producing some synthetic liquid fuel and wax at Leipzig in conjunction with the manufacture of city gas, and the equipment for accomplishing this was about 75 percent constructed by April 1945.

The plan was to pass a portion of each of the gases (water gas and oven gas) through Fischer-Tropsch converters, wherein CO and H_2 would react catalytically to form hydrocarbons, remove the liquid hydrocarbons thus formed, and blend the residue gas from the converters with the remainder of the manufactured gas for city distribution. Although this plant was not in operation at the time of the author's visit, the results that were anticipated, based upon experience in the operation of such converters elsewhere in Germany, are indicated in table 5.

An analysis of the data shown in table 5 indicates that 1,000 cubic feet of synthesis gas (column 3) would produce 500 cubic feet of residue gas (column 4), which later would have a calorific value of substantially 450 B.t.u. per cubic foot, which is an increase of 35.6 percent. In forming this residue, gas hydrocarbons and water also are formed, which do not appear in the gas analysis. Calculations show that for each 1,000 cubic feet of synthesis gas converted as shown in table 5, 4.50 pounds of carbon and 1.63 pounds of hydrogen are removed from the system (from the gas) and presumably form hydrocarbons and water by the Fischer-Tropsch reactions. From these figures, it can be approximated that the amount of motor fuel and some higher molecular-weight hydrocarbons formed would be about 4.85 pounds per 1,000 cubic feet of synthesis gas treated. Thus, a gas plant producing 14,694,000 cubic feet of combined water gas and oven gas (as in columns 1 and 2) per day, with a calorific value of 387 B.t.u. per cubic foot, would yield, according to table 5, 10,602,000 cubic feet of city gas having a calorific value of substantially 426 B.t.u. per cubic foot and hydrocarbon byproducts (chiefly motor fuel and wax) amounting to about 39,700 pounds per day.

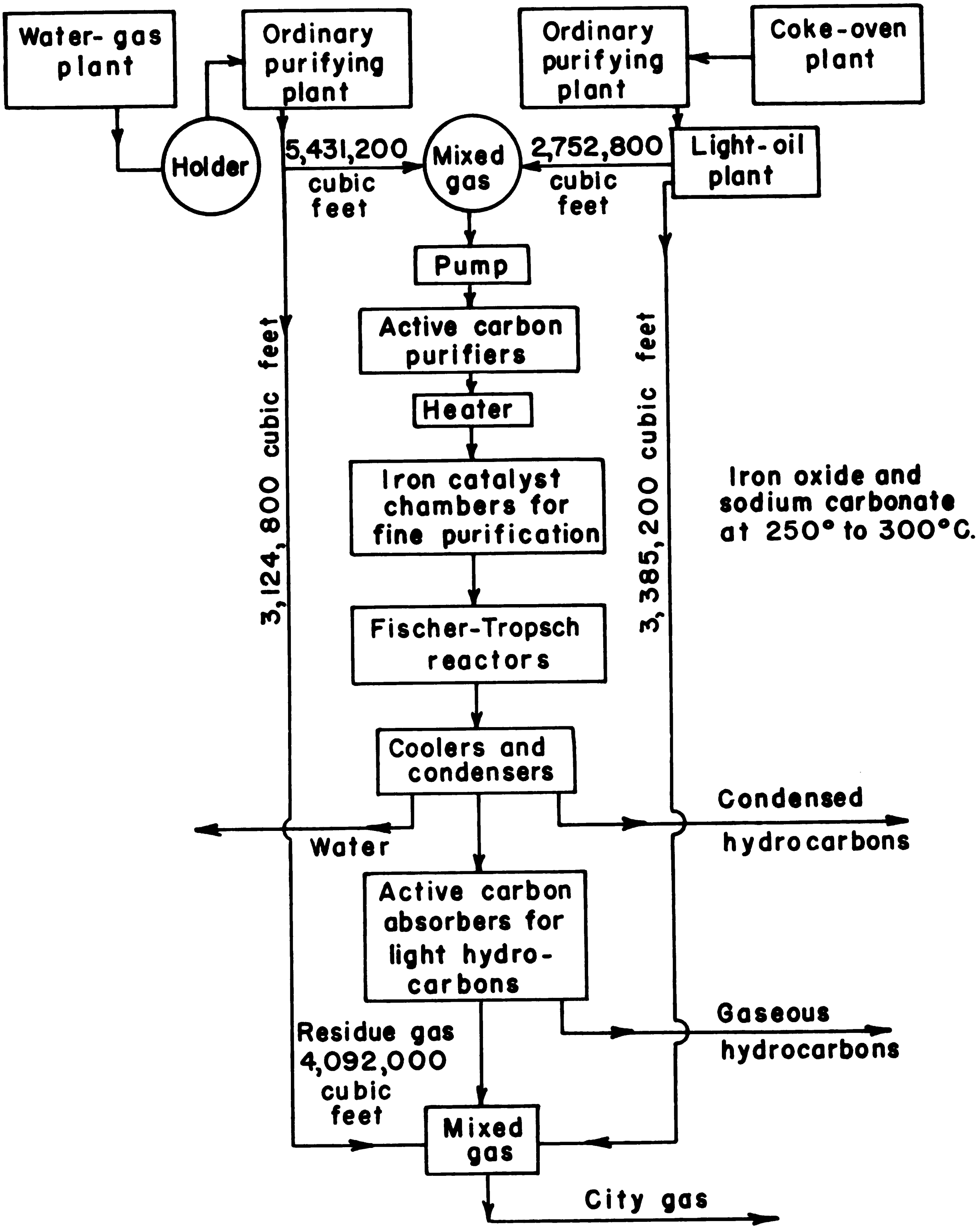

Figure 12.- Diagram of the flow of gases through the conversion and gas-treating units of a Fischer-Tropsch plant making city gas.

TABLE 5. - Data relating to the production of city gas and liquid fuel from oven gas and water gas in Fischer-Tropsch converters

	1	2	3	4	5
	Oven gas	Water gas	Mixed gas to converters (synthesis gas)	Residue gas	City gas
Oven gas..........	-	-	2,752,800	-	3,385,200
Water gas.........	-	-	5,431,200	-	3,124,800
Residue gas.......	-	-	-	-	4,092,000
Volumes, cu.ft. per day..........	6,138,000	8,556,000	8,184,000	4,092,000	10,602,000
Composition of the gases:					
CO_2.............	2.4	5.0	4.1	8.1	5.4
Illuminants....	1.2	-	0.4	1.0	0.8
O_2..............	0.4	-	0.1	-	0.1
CO.............	5.7	38.0	27.2	21.3	21.2
H_2..............	59.0	52.0	54.3	37.5	48.6
CH_4.............	27.8	0.3	9.6	23.6	18.1
N_2..............	3.5	4.7	4.3	8.5	5.8
	100.0	100.0	100.0	100.0	100.0
Specific gravity..	-	-	0.4640	0.5805	0.49
Calorific value, B.t.u. per cu.ft. (dry gas)........	516	294	368.7	449.9	425.8
B.t.u. per cu.ft. sat. at 60° F. ..	507	289	361.3	442.1	418.4

It appears that in the combined operations described, not only would the daily output of gas in cubic feet be less than the total water gas and oven gas made, but, also, the heating value of the total city gas produced would be approximately 79.6 percent of that of the latter gases. In other words, in order to produce enriched gas and liquid hydrocarbons on a basis indicated by the data presented in table 5, it would be necessary, for the daily production of a unit number of therms in the city gas, to increase the gas-generating capacity appreciably above that required in making a similar city gas by mixing water gas and oven gas. The cost of this additional gas-making equipment plus that of the Fischer-Tropsch converters will occasion an increase in the cost per therm of city gas. The process can be economical when the increased costs are more than compensated by the value of the wax and the liquid and gaseous hydrocarbons produced. It would be most economical to employ this combination process when the cost of mixed water gas and oven gas is low and the prices of motor fuel, wax, and gas enricher are high.

Description of plant and proposed operating procedure

Figure 12 shows the flow of gases through the conversion and gas-treating units of a Fischer-Tropsch plant used in making city gas. The quantities of raw materials to be used and the conversions expected are those shown in table 5. A water-gas plant supplies water gas, and coke ovens supply the oven gas.

The mixed gas in the quantities indicated is to be compressed to somewhat more than three atmospheres pressure and then passed through activated carbon for removal of remaining traces of H_2S and gum-forming compounds and other impurities. For this purpose, 11,000 pounds of activated carbon will be used, distributed equally in three purifiers, which latter are steel vessels 7 feet in diameter and a little more than 10 feet high. These units are not to be operated in series; when one of them is in use treating the gas, one will be subjected to a steaming operation for revivification of the carbon, and the other will be under treatment for cooling the carbon. In this manner the operation will be conducted in 40-minute cycles; that is, each purifier will be used for treating gas 40 minutes, steamed 40 minutes, and cooled for a like period. Actually only one-third of the 11,000 pounds of carbon will be treating gas at any one time. The optimum temperature of the carbon while "on stream" (treating gas) is said to be 75° to 85° F., whereas the maximum allowable temperature during reactivation is 335° to 355° F., the desired temperature being 300° to 320° F., The cooling operation will be accomplished by circulating water-cooled residual gas through the steamed carbon bed.

Computations from the foregoing show that the total carbon to be used in the purifying boxes amounts to 1,344 pounds per million cubic feet of gas to be treated daily. Furthermore, since only one of three chambers will be "on stream" at any one time, all of the 8,184,000 cubic feet of mixed gas (synthesis gas) will pass daily through a purifier 7 feet in diameter; that is equivalent to a mean linear gas velocity of 0.69 foot per second at 80° F. and 39.5 pounds gage pressure, without allowing for space occupied by the carbon. The true linear velocity will approximate 1.65 feet per second. The carbon has a bulk density of 21.8 to 23.7 pounds per cubic foot and is made from brown coal. The pressure of the gas passing through the carbon bed, it is said, will decrease about 7.75 pounds; this pressure drop seems to be too high for the bed depth.

As shown in figure 12 the gas from the activated-carbon purifiers will pass through iron-oxide catalysts for final purification. It appears that the carbon does not remove all of the organic sulfur from the gas and that, in order to prevent rapid deterioration of the catalyst to be used in the converters, additional purification is necessary. For this purpose, a catalyst comprising iron oxide and sodium carbonate, confined in six steel purifiers, will be used. These purifiers are cylindrical, approximately 8 feet in diameter and 8 feet high, and each one has a capacity for confining 353 cubic feet of the iron catalyst. The gas supply to these purifiers, will be divided into two streams, so that the gas will not pass serially through all six of the boxes. Any box in the system can be shut off for replacement of the catalyst without interrupting operations. Means are provided whereby the gas will be so preheated before entering the purifiers that a "working temperature" in the catalyst mass will be 480° to 570° F. Under these conditions organic sulfur is converted to hydrogen sulfide, which, in turn, is oxidized and forms sodium sulfate by reaction with the sodium carbonate initially present in the catalyst. A small amount of O_2 must be present in the gas for the latter reactions to occur; it is to be added in amounts necessary when not already present. The loss in pressure occasioned by the resistance of the catalyst to passage of gas in traversing this purification system will be approximately 9.67 pounds. The catalyst used is granular.

After the latter purification, frequently designated "fine purification," the gas is to be passed directly to the Fischer-Tropsch converters (reactors) for the synthesis of hydrocarbons. These reactors, of which there are 12, are of the standard variety used in Germany and are 16 feet long, 9 feet high, and 6 feet wide. Each reactor has a capacity for confining 353 cubic feet of catalyst. It was the declared intention to use the "cobalt catalyst" having a density of about 22 pounds per cubic foot. The reactors were to be internally water-cooled by tubes imbedded in the catalyst mass. The 12 reactors were arranged in groups of 3, each group having a common overhead steam accumulator. The connections for the supply of synthesis gas were such that the gas would flow through each of the reactors in parallel, not in series. The water tubes were so connected in the system that the water condensate from the gas works would flow into the lower tubes, and then, by virtue of heat of reaction evolved in the catalyst bed, it would flow upward through the upper tubes to the overhead accumulator.

In operation of the reactors, the purified gas was to be supplied at about 23.2 pounds gage pressure, and the temperature in the catalyst mass was to be maintained at 365° to 392° F. Temperature in the catalyst bed is controlled by regulating the pressure in the accumulator and cooling system; gage pressures corresponding to 365° and 392° F. are approximately 149 and 211 pounds per square inch. The gases, upon reaction in the catalyst bed, are expected to yield approximately 550 tons of readily condensable hydrocarbon products per month, divided as follows: One-third benzine (light oil), one-third medium oil, and one-third wax. The anticipated yield was also reported as 100 grams of condensable products boiling at a higher temperature than the C_4 hydrocarbons per normal cubic meter of gas; this is equivalent to 5.92 pounds per 1,000 cubic feet of dry gas measured at 60° F. and 30 inches Hg. pressure. On this basis, the daily yield at rated capacity, as indicated in table 5, would be 8,184 x 5.92, or 48,449 pounds, equivalent to 24.2245 x 30, or 726.7 tons per month. The latter figure is higher than that given above (550 tons per month), indicating operations would not be continuously at capacity; but it is also higher than the yield computed by the author and given in the foregoing at approximately 4.85 pounds of total hydrocarbons removed from the system per 1,000 cubic feet of synthesis gas, which amounts to approximately 39,692 pounds per day or 595.38 tons per month. It appears reasonable to expect a yield of hydrocarbons having more than 4 carbon atoms per molecule amounting to about 550 tons per month with continuous operation of the plant.

The drop in pressure in the gas stream, between inlet and outlet of the reactors, will be about 9.67 pounds per square inch.

After the reactions have occurred in the reactors, the hot exit gases will pass into a common header, which leads to a cooling and water-scrubbing system adapted to cool the stream containing the reaction products by direct contact with water. The scrubbing system comprises 2 packed towers 30 feet high and about 4 feet in diameter, each confining 6 separate beds of Raschig rings 2-1/2 feet thick spaced 18 inches apart. The drop in pressure of the gas stream when it passes through the scrubbers will be about 0.97 pound. Separators are so arranged with reference to the scrubbers that the major portion of the readily condensable hydrocarbons will separate from the gas and be collected there.

The cooled gas stream will then be subjected to treatment with activated carbon (absorbent carbon), somewhat as described for purification, for removal and recovery chiefly of ethane, ethylene, propane, propylene, butanes, butylene, and pentanes. The residue gas, stripped of these hydrocarbons, will then be mixed with the excess water gas and oven gas as shown in figure 12.